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Use of Remote Sensing Techniques in a Systematic Investigation of an Uncontrolled Hazardous Waste Site

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USE OF REMOTE SENSING TECHNIQUES IN A SYSTEMATIC INVESTIGATION OF AN UNCONTROLLED HAZARDOUS WASTE SITE

by

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Contract No. 68-01-5051

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-- nature and extent of ground water contamination

-- presence and number of buried drums

-- topography and condition of bedrock

-- costs and effectiveness of several abatement methods.

Both the remote sensing and conventional sampling methods were used at an abandoned hazardous waste dump in Coventry, Rhode Island.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, reassuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report describes the use and evaluation of several remote sensing techniques in conjunction with direct sample collection in order to develop a systematic approach for subsurface investigations at uncontrolled hazardous waste sites.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

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- Geotechnical Engineers Inc. (consultants for bedrock coring and sampling)
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- Guild Drilling Co. (well installation and rock coring)
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SECTION 1

INTRODUCTION

Section 1 covers the purpose and scope of the work documented in this report, briefly introduces the remote sensing techniques used in the study, presents a brief history of the uncontrolled hazardous waste site which was investigated, and describes the results of the investigations undertaken.

PURPOSE AND SCOPE

This report describes the use and evaluation of several remote sensing techniques in conjunction with direct sample collection in order to develop a systematic approach for subsurface investigations at uncontrolled hazardous waste sites. It is one of two reports concerning the Coventry site which were prepared by The MITRE Corporation for the U.S. Environmental Protection Agency, Solid and Hazardous Waste Research Division (EPA/SHWRD). The second report, entitled "Evaluation of Abatement Alternatives: Picillo Property, Coventry, Rhode Island", (MITRE Technical Report 80W00253), represents the continuation of a site subsurface investigation initially funded by the Rhode Island Department of Environmental Management (DEM) and contains specific results, conclusions, and recommendations to the DEM for abatement actions.

Remote sensing techniques were employed to determine the extent (and sequence) to which they may be integrated with the more conventional methods of test drilling, installation of monitoring wells, and excavations for determining information such as the following:

- nature and extent of ground water contamination
- presence and number of buried drums
- topography and condition of bedrock
- costs and effectiveness of several abatement methods.

The following remote sensing techniques were used during an investigation of an abandoned hazardous waste dump site in Coventry, Rhode Island:

- electrical resistivity
- ground-penetrating radar
- seismic refraction
- metal detection.

Direct investigative techniques included:

- collection of soil and ground water samples through installation of shallow and deep monitoring wells
- collection of bedrock samples
- collection of surface water samples
- chemical analysis of water and soil samples for priority pollutants and total volatile organics
- excavation of buried drums of chemical waste.*

Neither list is intended to be an exhaustive summary of the available techniques, especially the remote sensing methods, which could be used in an investigation of this type. The investigative techniques are not, in themselves, unusual, each having been employed previously in a similar application (see next subsection). The important aspect of this study is that the remote sensing and direct data collection techniques were applied in combination, which enabled a broad yet thorough understanding of the situation prior to the recommendation of the most suitable alternative for abatement of site pollution.

Section 2 of this report describes how the previously listed remote sensing techniques were applied at the Coventry site and Section 3 presents the results obtained. Advantages and limitations of each method are discussed and evaluated in Section 4 and recommendations concerning investigations at other sites and research needs are presented in Section 5.

SUMMARY OF THE REMOTE SENSING METHODS

Electrical resistivity surveying is a remote sensing technique that, when employed as part of an investigation of an abandoned waste site, may be used to locate the lateral and vertical extent of ground water contaminated with ionic species and to monitor the movement of the contaminant plume with time. The technique has often been used in ground water contamination studies. Resistivity measurements are taken from the ground surface using portable equipment and are used, for example, for determining the most advantageous placement of monitoring wells. The method cannot be universally employed however, as both natural conditions and man-made obstacles may affect its success at a particular location.

Seismic refraction techniques have been applied to the exploration of new ground water supplies and seismic refraction surveying has three potential uses at an uncontrolled hazardous waste site:

- determination of bedrock topography in order to locate the position of deep wells to bedrock and cost of interceptor trenches

*Conducted and funded by the Rhode Island Department of Environmental Management.

- determination of boundaries of large numbers of buried drums for the purpose of estimating their number

- determination of soundness (extent of fracturing) of bedrock to evaluate its effectiveness as an impermeable base for leachate interceptor trenches or constructed physical barriers.

Metal detection and ground-penetrating radar may be utilized remotely to locate buried drums or other underground objects of interest. The two techniques effectively complement each other because they differ in information obtained, ease of use, interpretation of data, and cost. Radar also has the potential to provide limited data of a qualitative nature related to the condition and approximate density of buried drums, to the construction of trenches in the earth, and to the location of soil heavily contaminated with leaking chemicals. It has been applied in various situations, such as to locate buried sewer lines and cables or to determine the thickness of sea-ice. Ground-penetrating radar was used during the early stages of the investigation at Love Canal, and its application at abandoned hazardous waste sites appears to be increasing.

HISTORY OF THE SITE

The abandoned hazardous waste dump site which was investigated is located in Coventry, Rhode Island, approximately 20 miles southwest of Providence. The site encompasses approximately 7.5 acres of cleared ground surrounded by woods and wetland in a relatively rural area of the state (see Figure 1). An undetermined quantity of chemicals had been placed into the ground both by the burial of 55 gallon drums in five separate locations and by direct discharge into trenches (see Figure 2). There are approximately 30 to 40 dwellings within a one-mile radius of the dump site, but none in the downgradient area of discharge. A swamp, 1,200 ft to the northwest of the site, is the surface discharge area of chemicals leaching from the dump. This swamp discharges to a body of water called Whitford Pond which is a source of irrigation water for a cranberry bog located approximately one mile from the swamp's outlet. To date, no evidence of chemical contamination in Whitford Pond has been found, based on sampling conducted by the DEM and the U.S. Environmental Protection Agency (EPA), Region I.

State of Rhode Island officials were alerted to the dumping activities by a fire and explosion on September 30, 1977. A court order issued on November 18, 1977 prohibited the property owner (Warren Picillo) from continuing dumping activities or otherwise altering the site. From the end of 1977 to mid-1979, the DEM conducted field investigations to quantify the seriousness of the situation.

In October 1979, the DEM contracted with The MITRE Corporation to conduct a systematic site assessment, and in April 1980 the investigation continued under funding by the EPA/SHWRD. Although the investigation of the Coventry site was conducted in two discrete phases with separate project reports, overall project continuity was maintained. Phase I funding was shared by the DEM and EPA/SHWRD* and Phase II was completely undertaken by EPA/SHWRD.

*EPA/SHWRD funded all chemical analysis and the preliminary evaluation of abatement methods.

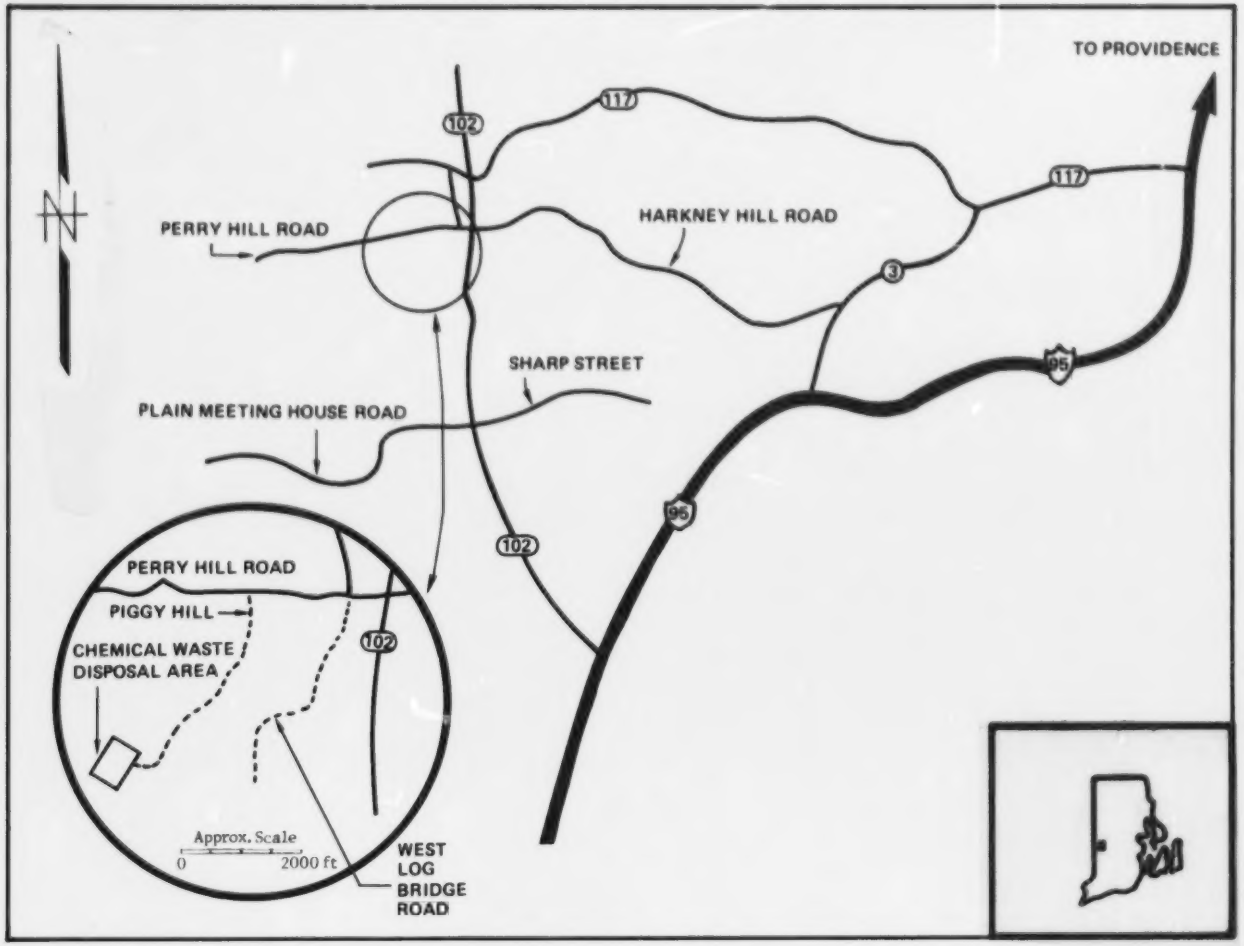

Figure 1. Location of the Hazardous Waste Dump Site in Coventry, Rhode Island

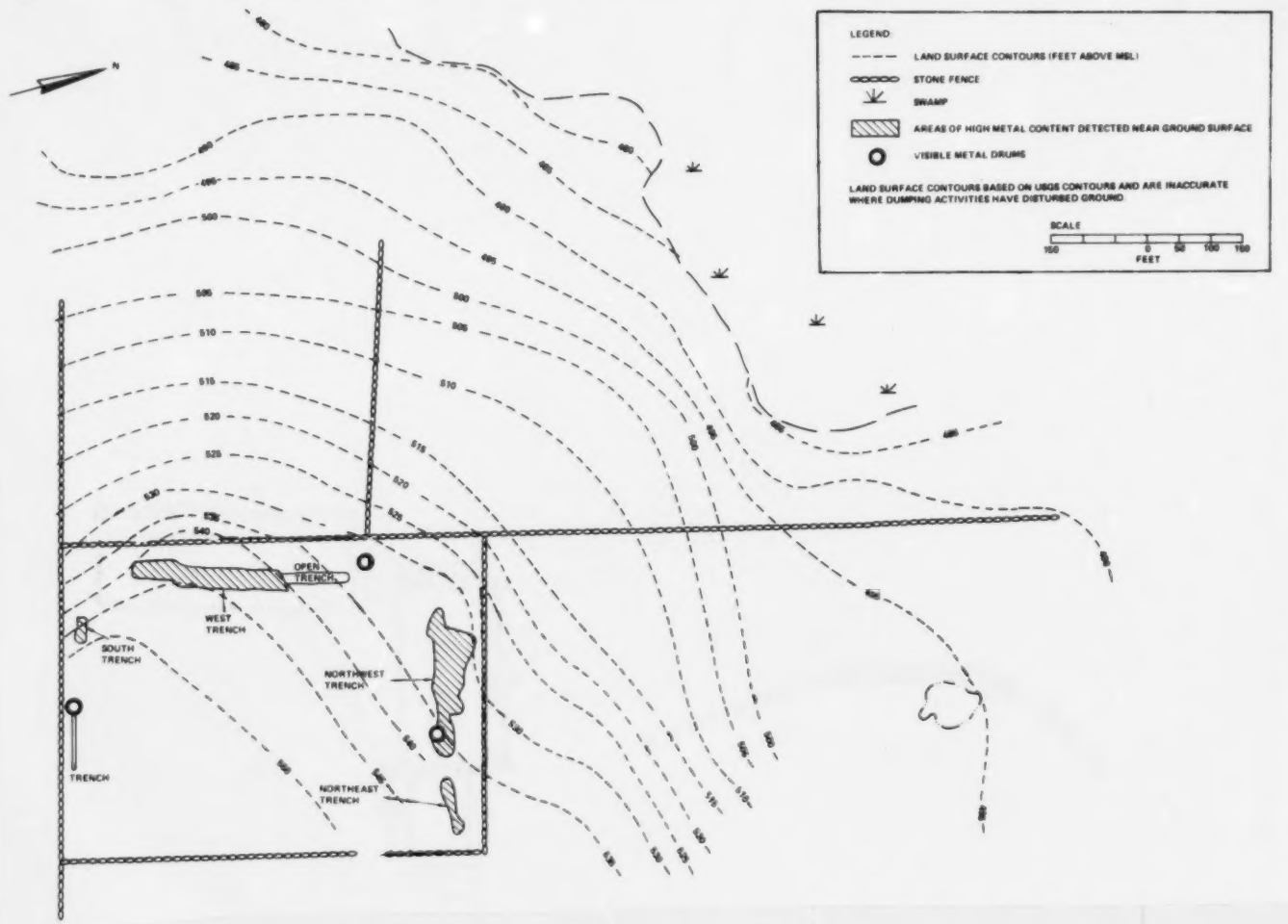

Figure 2. Outline of Trench Locations at the Coventry Site as Determined by Metal Detection Survey

SITE INVESTIGATION: PHASE I AND PHASE II

The overall purpose of the Phase I and Phase II investigations was to: a) determine the nature and extent of a problem consisting of buried drums and subsurface chemical contamination; and b) evaluate the potential costs and effectiveness of the following abatement methods:

- site encapsulation
- leachate collection and treatment
- drum removal and disposal

as well as of the "no action" alternative.

The techniques employed for data collection during the Phase I effort were: electrical resistivity; metal detection; installation of monitoring wells; and chemical analysis of soil, ground water, and surface water. The field methods employed, data collected, conclusions drawn, and recommendations made to the DEM are documented in the Phase I project report: "Hazardous Waste Investigation: Picillo Property, Coventry, Rhode Island", April 1980 (MITRE Technical Report 80W00032). Although the extent of the problem was defined and abatement options were preliminarily evaluated, certain key pieces of information (concerning the presence of fracturing or contamination of the bedrock and the condition and number of the buried drums) needed to be ascertained before a permanent solution could be selected. The Phase I report presented the abatement options, identified the necessary additional information, and made recommendations for immediate and near-term actions to protect the public health and to collect additional data. Summaries of the principal conclusions, recommended actions, and comparison of abatement methods are presented in Appendix A.

The relationships among the abatement methods, the additional information needs at the conclusion of the Phase I study, and the techniques employed in Phase II to obtain that information are shown in Table 1. Phase II was undertaken by MITRE with EPA/SHWRD funding (ground-penetrating radar, seismic refraction, bedrock sampling, and chemical analysis) and by the DEM under internal state funding (exploratory excavation of Northeast Trenches). These activities and their purposes are summarized in Table 2.

The recommendations concerning long-term abatement methods determined from the Phase II field activities are contained in Appendix B.

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Table 1

Techniques Used in Phase II to Provide Information Needed to Select an Abatement Alternative

Alternative Action	Additional Information Required at end of Phase I to Select Alternative	Phase II Technique to Obtain Information*
1. No Action	• condition of source (drums) • state of nearby pond • contaminant underflow at swamp • ultimate disposition of all pollutants	• radar, exploratory excavation • additional wells, chemical analysis of soils and water samples
2. Drum Removal and Disposal (excavation, testing, and proper disposal of drums and contents, and contaminated soils)	• condition of source (drums) • condition of soil	• radar, exploratory excavation • exploratory excavation, chemical analysis of soil samples
3. Site Encapsulation (construction of impermeable barriers around source of pollutants)	• condition of source (drums) • condition of bedrock	• radar, exploratory excavation • seismic refraction, core drilling, deep wells
4. Leachate Collection and Treatment		
a. Limited Option (interceptor trenches constructed adjacent to site walls)	• condition of source (drums) • condition of bedrock	• radar, exploratory excavation • seismic refraction, core drilling, deep wells
b. More Complete Option (interceptor trenches constructed 600 feet downgradient of site walls)	• same as above	• same as above

*Metal detection had previously been used to locate trenches; electrical resistivity to delineate leachate plume. Radar could have been employed in lieu of or in conjunction with metal detection, as recommended for other sites; potential radar effectiveness was unknown at the time of the initial survey.

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Table 2

Field Activities
Picillo Property, Coventry, Rhode Island

Phase	Activity	Purpose
I.[a]	• lateral electrical resistivity profile	• location of plume • placement of monitoring wells
	• metal detection survey	• location of buried drums
	• soil, ground, and surface water sampling	• determination of ground water elevations • determination of occurrence and type of contamination
II.[b]	• ground-penetrating radar	• elaboration of number and location of buried drums
	• limited excavation of buried drums[c]	• determination of number and condition of drums
	• seismic refraction survey	• determination of bedrock profile • evaluation of potential to determine lower boundary of buried drums • estimation of soundness of bedrock
	• bedrock sampling	• determination of soundness of bedrock • determination of contamination of bedrock
	• surface and ground water sampling	• elaboration of subsurface contamination
	• vertical electrical resistivity profile	• evaluation of potential to determine lower boundary of buried drums

a. Funded by the Rhode Island Department of Environmental Management.
b. Funded by the EPA/SHWRD.
c. Funded and conducted by Rhode Island Department of Environmental Management.

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SECTION 2

REMOTE SENSING TECHNIQUES

Section 2 gives a brief description of each of the remote sensing techniques employed during Phases I and II at the Coventry site, including discussions of the equipment, other previous applications, and the specific procedures used in the field.

ELECTRICAL RESISTIVITY

The electrical resistivity of a geological formation depends upon the conduction of electric current through the particular subsurface materials. Since most of the geologic formations that contain water have high resistivities, the electrical resistivity of a saturated rock or soil is primarily a function of the density and porosity of the material and the concentration of the conducting ions within the saturating fluid. In a resistivity survey, an electric current is passed into the ground through a pair of current electrodes and the potential drop is measured across an inner pair of potential electrodes. The "apparent resistivity" is determined by the equation, $R_a = 2\pi A(V/I)$, where A is the electrode spacing, V is the potential difference, and I is the applied current. The depth of penetration is controlled by the distance between the electrodes (called the A-spacing) and is approximately equal to half of this distance.

Resistivity measurements can be taken in the form of either lateral or depth profiling. In lateral profiling, the Wenner electrode configuration is used, where the A-spacing is fixed and the electrodes are moved ahead in a straight line. This method allows lateral converage at a more-or-less constant depth, and can be used to define aquifer limits or to delineate variations in ground water quality. To obtain a depth profile, a series of measurements are taken at different electrode spacings to the left or right from a centralized electrode. This technique is called the Lee modification of the Wenner electrode array. Plotting the apparent resistivity against the electrode spacing gives an indication of the resistivity of various layers at successively greater depths. Interpretation is most successful in areas having a simple layered structure since the apparent resistivity is a measure of the effects of all the layers between the maximum depth of penetration and the surface. Depth profiling has often been used to determine the thickness of glacial aquifers overlying bedrock and to locate the saltwater/freshwater interface in coastal aquifers. Additional information regarding the electrical resistivity technique may be found in U.S. EPA (1978) or Freeze and Cherry (1979).

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Both lateral and depth profiling surveys were conducted at the hazardous waste site in Coventry using a Bison Instruments Model 2350B Earth Resistivity meter powered by a 90-volt battery. An electrode spacing of 20 feet was used for the lateral profiles in the areas of the trenches and the swamp where the depth of ground water contamination was suspected at 10 to 15 feet. Two lateral profiles using an A-spacing of 50 feet were also conducted approximately 2000 feet west and north of the immediate site walls, where it was suspected that the contamination might be detected at depths of 25 to 35 feet.

Additionally, seven depth profiles using the Lee modification were conducted in the vicinity of a large trench containing buried drums located by the metal detection survey near the western boundary of the site. Electrodes were set at intervals of 1, 2, 4, 8, 16, and 32 feet at each profile location, permitting a maximum depth of investigation of approximately 15 feet. Resistivity readings were taken at each spacing interval for the left, right, and central spacings. This particular spacing interval was chosen based upon the intents of the investigation, which were to identify changes in subsurface contamination and to locate the boundary defining the bottom of the trench.

The lateral surveys were conducted by Fred C. Hart and Associates, Inc. and the vertical surveys by Stephen A. Alsup and Associates, Inc.

SEISMIC REFRACTION

The seismic refraction method is based on the principle that elastic waves (mechanical rather than electromagnetic) travel through different subsurface strata at different velocities. Elastic waves are introduced to the ground surface by an energy source, usually a small explosion or a hammer blow on a steel plate for shallow investigations. The refracted waves are detected by small seismometers (geophones) located on the surface at various distances from the energy source. A seismograph records the travel time between the vibration and the arrival of the elastic wave at the geophones. Plotting arrival time versus distance from the energy source to geophone from a series of seismograph records enables the determination of strata depths and their seismic velocities through the use of simple refraction theory. Greater detail concerning geophysical surveys may be found in Dobrin (1960).

Seismic surveys have been used in hydrogeologic investigations to provide subsurface geologic information, such as depth to bedrock and presence of buried bedrock valleys, more rapidly and at lower cost that could be determined through actual test drilling. Interpretation of seismic data, however, is difficult in areas having complex stratigraphy or stratigraphy exhibiting little contrast in propagational velocities. In addition, propagational velocities within the subsurface layers must increase with depth because low-velocity layers that underlie high-velocity layers are completely obscured by the refraction of the high-velocity layer. For these reasons, limited test drilling should be conducted in conjunction with the seismic method to confirm the subsurface geologic interpretation.

Seismic refraction profiling of approximately 2,850 linear feet was performed at the Coventry site in two days of field work. Figure 3 shows the

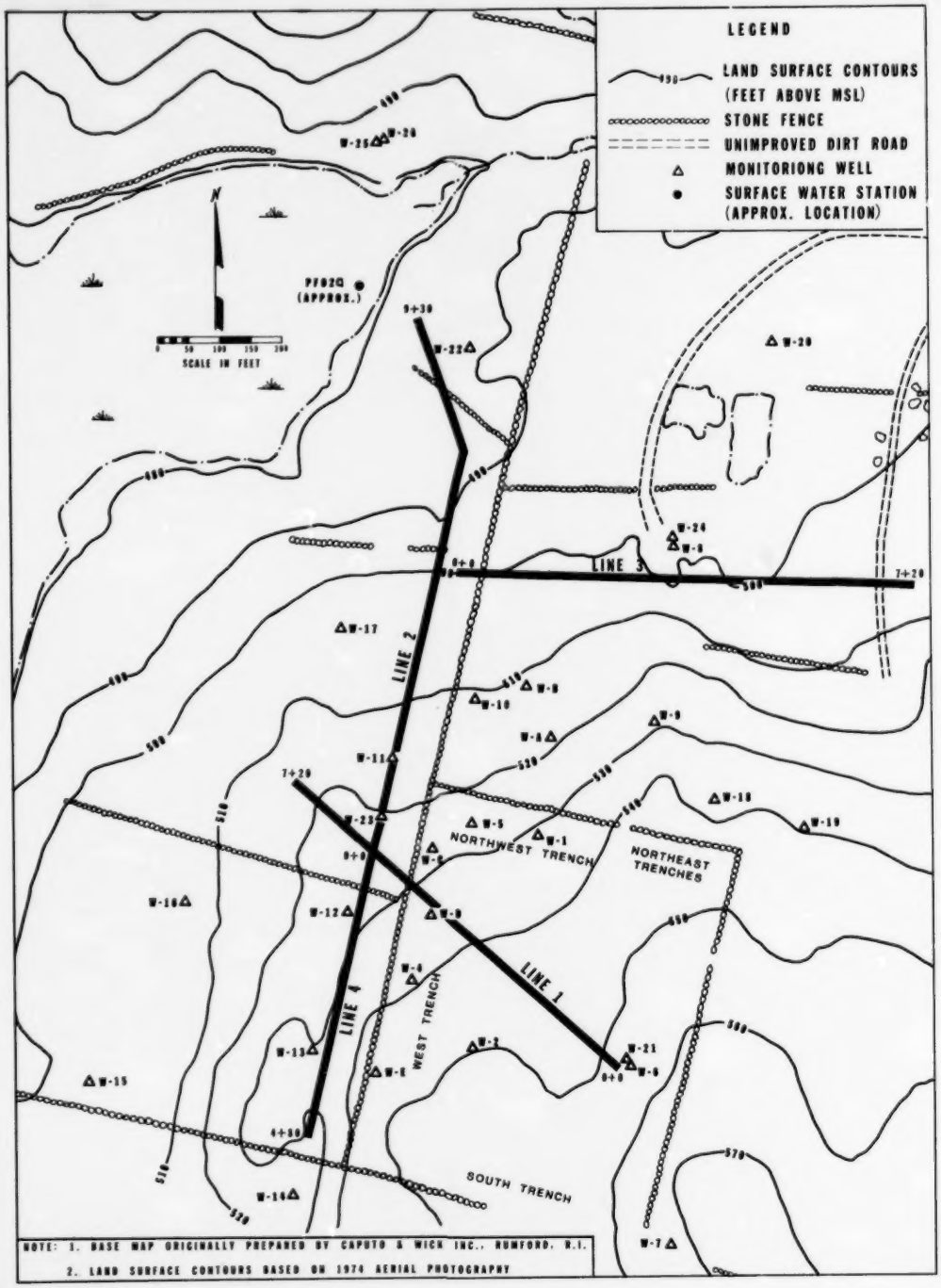

Figure 3. Approximate Location of Seismic Refraction Profiles (lines not surveyed)

location of seismic profiles. A Geometrics/Nimbus Model ES1210F Multichannel Seismograph was used to record and collect the voltage outputs from 12 Mark Products L-15 vertical geophones spaced at 20-foot intervals for each refraction spread. The energy source used to initiate each record and shock wave was a 30-pound weight drop or 10-pound sledge hammer blow on a steel plate with an attached impact start switch. The Model ES1210F Seismograph, which includes a digital memory of waveform from each data channel, allows repetitions of the elastic waves from a series of hammer blows thereby enhancing the ability to detect signals and pick arrival times. The use of the hammer drop as the energy source (which is preferable for safety reasons to using small explosive changes in this type of investigation) would be more difficult without the digital memory of the seismograph. Impact points for this survey were at the end of, and quarterly along, the refraction spread, providing a locus for depth calculations at 80-foot intervals along each spread. Data continuity and repetition were achieved by repeating end shots where refraction lines were longer than one spread length.

The seismic refraction survey was conducted by Stephen A. Alsup and Associates, Inc.

METAL DETECTION

The entire 7.5 acre site in Coventry was surveyed by personnel from Fred C. Hart and Associates, Inc., with a Fisher M-Scope (Model TW-5) metal detector. This equipment is designed for locating buried metal objects by inducing an electromagnetic field around the object in response to radiation from a transmitter. The average depth of detection for metal objects is dependent on the amount of background "noise." Thus in areas free of buried metal, the probable depth of detection for metal objects was approximately six to eight feet. In areas of buried drums, the sensitivity setting of the instrument had to be cut back, resulting in a potential depth of metal detection of approximately four to five feet. In areas where buried drums were suspected, based on disturbed ground or the initial gross scan of the overall site, the survey was conducted by traversing closely spaced grid lines.

GROUND-PENETRATING RADAR

The technique of ground-penetrating, or impulse radar involves the repetitive propagation of short-time duration (on the order of a few nanoseconds, nsec) pulses of electromagnetic energy in the radar frequency range downward into the ground from a broad bandwidth antenna on (within a few inches of) the surface. Reflections from subsurface interfaces are received by the antenna during the off-period of the pulsed transmission, processed electronically, and recorded to yield a continuous profile of subsurface conditions as the antenna/transmitter-receiver unit is moved across the ground surface.

The depth to an interface, or the surface of a "target" such as a metal drum, is determined by measuring the time for a radar pulse to travel to the interface and reflect back to the surface. In air, radar travels at the speed of light or about one nsec/ft. Typical speeds in soil range from six nsec/ft for drier soils to eight nsec/ft for wetter soil conditions, hence depth calibration would be based on a round trip velocity in the range of 12 to

16 nsec/ft of depth. A real-time display of the depth profiles can be obtained for field interpretation using a strip-chart recorder, and the data can be recorded more completely and permanently on magnetic tape for subsequent playback and interpretation.

Impulse radar has been used as a geophysical technique in such applications as surveying archeological sites, locating sewer lines and buried cables prior to construction activities, and profiling lake and river bottoms (see Morey and Harrington (1972) and Campbell and Orange (1974)). The application to locating buried drums of chemical wastes is relatively new, and further refinements both in the technology and in data interpretation are anticipated.

The field survey was conducted by the equipment manufacturer, Geophysical Survey Systems, Inc. (GSSI). The equipment used was GSSI's SIR System 7 ground radar. The survey of the trench areas, representing approximately two acres, took two days. Following experimentation with two alternative antennas and center frequencies, GSSI Model 3105AP operating at a center frequency of 300 MHz and GSSI Model 3102 operating at 600 MHz, the latter was chosen for most of the survey due to its improved spatial resolution at shallower depths. The operating depth varies approximately as the inverse square of the frequency, all else being equal.

One large trench (labelled the West Trench on Figure 2) located by the metal detection survey was surveyed with the 300 MHz antenna set at a nominal depth of 25 feet, later calibrated at 24.4 feet, based on average soil conditions. The other trenches (labelled Northwest, Northeast, and South) were subsequently surveyed using the 600 MHz antenna set at a nominal depth of 12.5 feet. The survey was conducted according to a rectangular grid. All trenches were surveyed longitudinally by using parallel radar transects at spacings of ten feet. Transverse transects, or cross-cuts, were made at intervals of 20 feet for the Northeast Trench and 40 feet for the West and Northwest Trenches. The antenna unit was pulled along each transect manually, and the data recorded by wire connection with equipment located in a stationary van on the site, which also served as the power source. The major equipment components were a control unit with cathode ray tube display, a tape recorder, a graphic (chart) recorder, and a solid state inverter.

The radar beam has a spread of $\pm 45^{\circ}$ in the fore and aft directions, and $\pm 20^{\circ}$ laterally. Any target detected within this beam will be recorded as being directly below the point of the surface where the signal is transmitted and received, and signals are reflected only from surfaces perpendicular to the direction of the signal. The use of a 10-foot grid spacing thus resulted in a sampling approach, as opposed to full coverage of the subsurface volume. However, even with a very fine grid, a fraction of the buried drums would be missed by the radar due to (a) their orientation or (b) their being "shielded" by metal drums closer to the surface, since metal is a near-perfect reflector of radar energy.

Illustrative data from the survey are shown in Figures 4, 5, and 6. The ground surface is at the top of each figure whereas the bottom of the figure corresponds to a depth of approximately 12 feet. The vertical dashed lines

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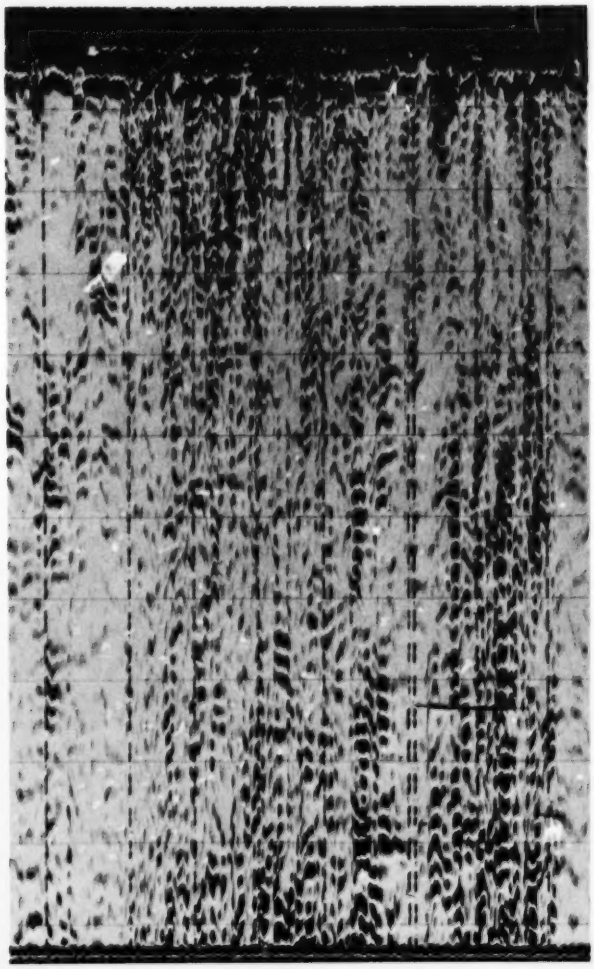

Figure 4. Radar Profile Taken Outside Trench Boundary

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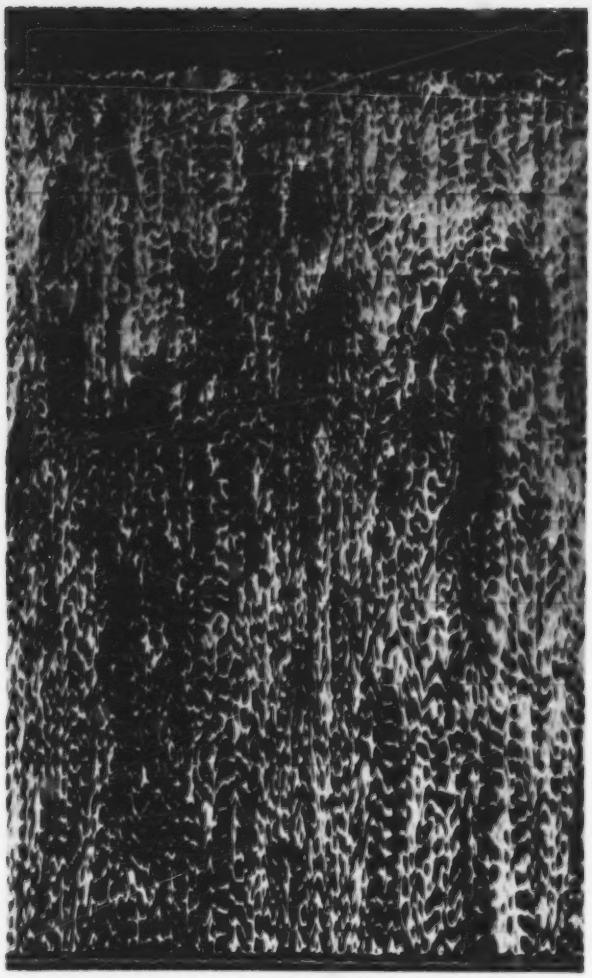

Figure 5. Radar Profile Taken Within Trench Boundary Showing "Signatures" of Buried Drums

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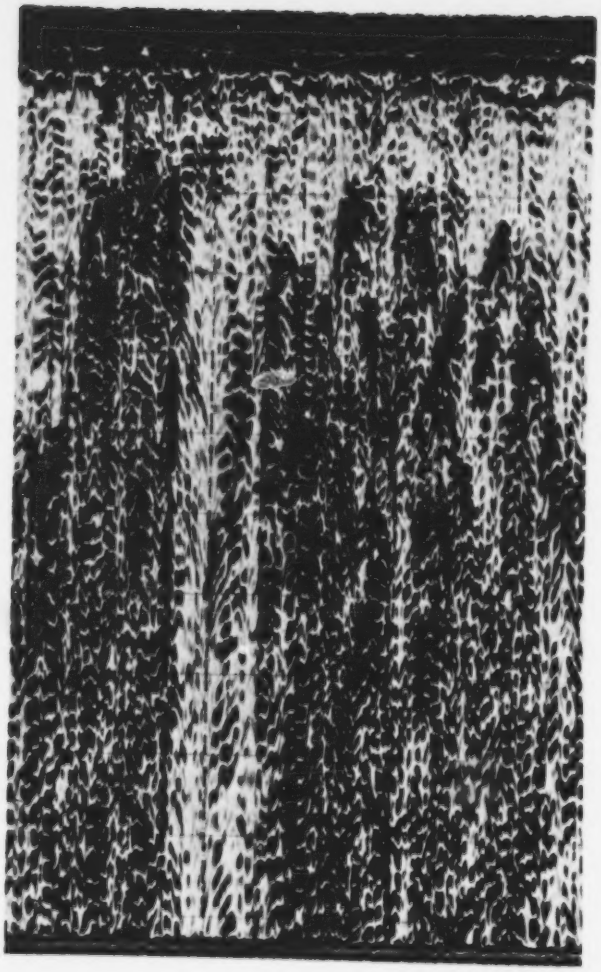

Figure 6. Radar Profile Taken Within Trench Boundary Showing Buried Drums and Suspected Chemical Contamination (Blurriness in Left-Center of Photo)

are markers produced electronically in the field, which correspond to 10-foot intervals. Figure 4 illustrates a subsurface profile where there are no buried drums. This profile was taken over an area of undisturbed soil.

In Figure 5, there are a number of individual targets identifiable by the characteristic hyperbolic "signature." This signature results from the increased travel time between the target and the antenna when the beam approaches or moves away from the target versus when it is directly over the target. Each reflecting target will produce three characteristic hyperbolas. It is possible for a skilled interpreter to distinguish between the signature caused by a drum or boulder either in the field or from the recorded data. In the field, a metal object can be determined instrumentally by comparing the polarity of the target signal to the background signal. A metal object which is essentially a perfect reflector, will produce a signal that is "in phase" with background. An object such as a boulder will produce a signal reversed from background. Close examination of the recorded data will also show another reflecting signal produced by a metal object in addition to the three characteristic hyperbolas. This fourth image found above the characteristic three is also caused by the reflection from metal and would not be present on the data if the target were a boulder.

Figure 6 shows a blurred effect which is interpreted as being caused by a concentration of contaminants, as from a leaking drum. Chemical analysis by the DEM has shown that some of the chemicals being released from the drums were ionic, which is a characteristic that would increase the attenuation of the radar signal strength. Therefore a noticeable blurred contrast relative to the average signal strength is observed on data taken over a trench containing a high concentration of contamination.

SECTION 3

RESULTS OF FIELD STUDIES

Section 3 describes the results of field studies at the hazardous waste dump site in Coventry.

PLUME DELINEATION

Having determined the information needed to evaluate the long-term abatement alternatives, a Phase I hydrogeologic investigation was planned to achieve certain general objectives. Those objectives were:

- to identify the source of contamination and type of contaminants in soil and water
- to define the areal extent of ground water contamination and the direction of flow
- to determine the quantities of contaminated ground water flowing away from the site.

A principal component of the site investigation was the installation of shallow monitoring wells in order to collect soil and water samples and to determine ground water elevations.

Because natural conditions at the site were such that measurement of electrical resistivity was expected to be successful (see Section 4), a lateral profiling survey was performed to facilitate the placement of monitoring wells and a depth profiling survey was conducted to determine vertical contamination patterns. The surficial geology map of the particular quadrangle on which the site was located showed that the area was characterized by a relatively thin mantle of till or outwash overlying crystalline bedrock. Nine monitoring wells previously installed on top of the site by the property owner indicated a shallow unconfined aquifer within the glacial deposits, with the direction of flow toward the swamp. A surface water sample analyzed by the State of Rhode Island in the summer of 1979 showed above average concentrations of iron and chloride, both of which would increase the conductivity of the ground water. All of these factors: shallow water table, generally uniform unconsolidated material overlying crystalline bedrock, and sharp contrasts between contaminated and natural water, indicated that the resistivity method could be used to establish the lateral and vertical extent of the ground water contamination. The information obtained could then be used to aid the selection of locations for additional monitoring wells.

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Figure 7 shows the apparent resistivity values obtained during the lateral profiling survey, plotted on a contour map. The measurements taken using both the 20- and 50-foot A-spacing are given. Rather than showing that the plume was moving directly toward the swamp in a northwesterly direction as suspected from measurement of water levels in existing monitoring wells, the apparent resistivity values gave an indication of two distinct plumes (a western and a northern plume) at different depths with each having a separate source. With increasing distance from the site, however, the two plumes joined finally to discharge in the swamp.

The western plume, which was defined primarily using the 20-foot A-spacing, appears to be generally within 10 feet of the surface. Most of the plume moving toward the north was defined using the 50-foot A-spacing and appears generally deeper than 20 feet below the surface. However, some shallow contamination is also apparent along the northern border of the site near the trenches. Shallow bedrock off the northwest corner of the site was considered the most likely explanation for the high apparent resistivity values between the two plumes, although this explanation was later proven to be false (see next subsection). Hence, the results of the resistivity survey suggest that additional monitoring wells be located to determine the existence of the shallow bedrock and to substantiate the presence of two separate plumes.

Additionally, a discovery of a contaminant source along the partly grass-covered western edge of the site was important information, since it served to indicate how far south and west the monitoring well program ideally should extend. As discussed in Section 2, locating this additional source of contamination may also have been possible using the radar technique based upon comparison of signal strength.

As mentioned earlier, several depth profiling resistivity surveys were conducted in the vicinity of the West Trench to determine vertical changes in contamination. Figure 8 is a plot of the apparent resistivity versus approximate depth below the surface (computed as half of the A-spacing) for several profiles taken over and outside of the trench boundary. Presentation of the data in this manner allows comparison of the "normal" or background resistivity patterns observed outside the West Trench where no contamination is expected, to the patterns observed over and downgradient from the trench where the occurrence of contamination is anticipated.

Profiles 1 and 6, taken outside the major plume boundary, as indicated by the lateral resistivity survey, are indicative of background patterns. Profile 2 was taken in the open, unfilled trench where no drums were buried, but bulk chemicals were suspected to have been discharged. This profile shows the effect of free-standing water in the trench and perhaps some slight contamination within the first few feet of the surface, and then an increase in resistivity to near background conditions. This indicates that either the open trench was not used for bulk dumping of significant amounts of chemicals with high electrical conductivity (since conductive effects decrease rapidly below several feet of depth), or that significant portions of the chemicals have been removed by leaching. Profiles 3, 4, 5, and 7, taken over or downgradient from the West Trench, show the varying degrees of contamination within the plume. A very high concentration of drums may explain the extremely low

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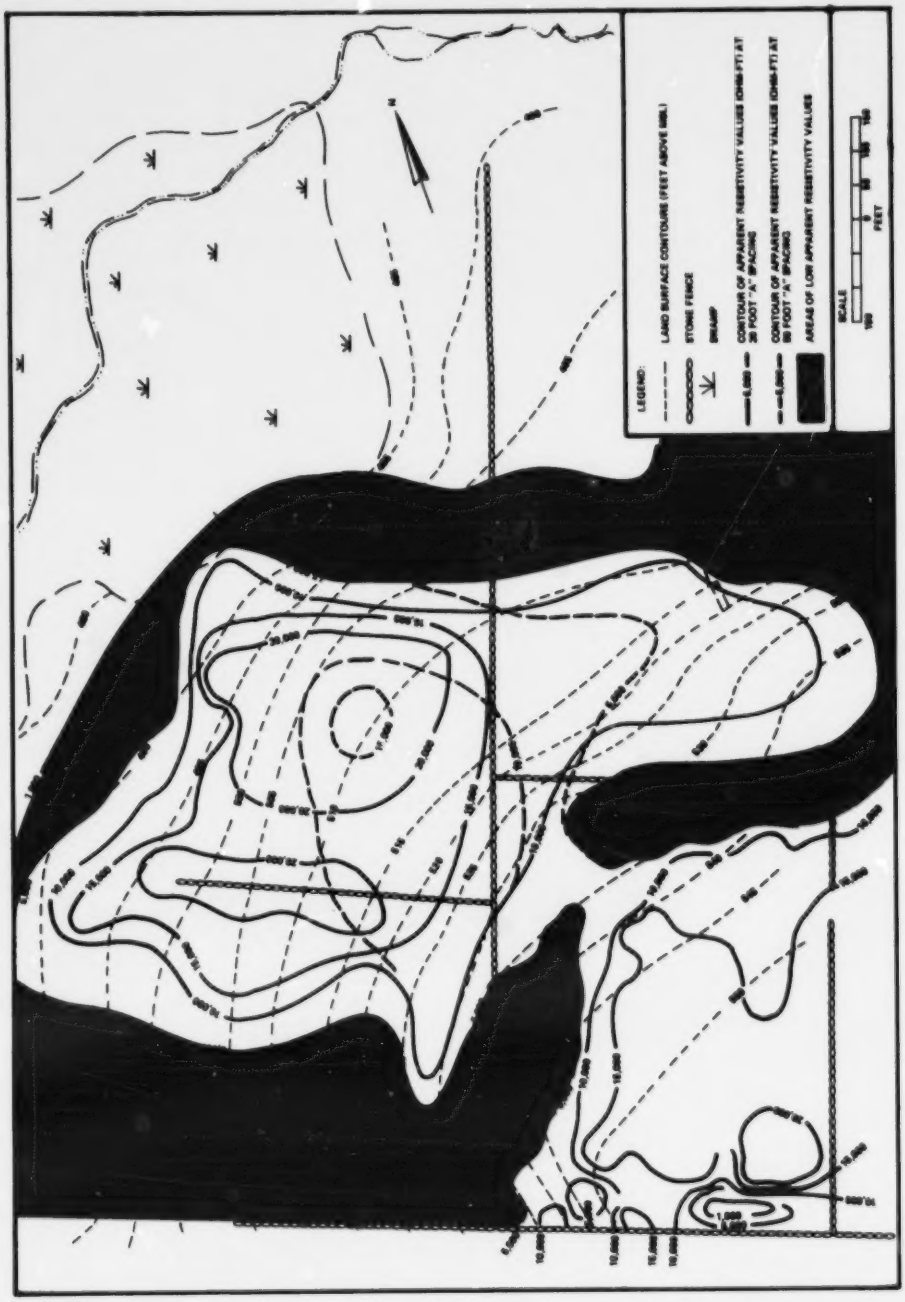
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Figure 7. Contour Map of Apparent Resistivity Values

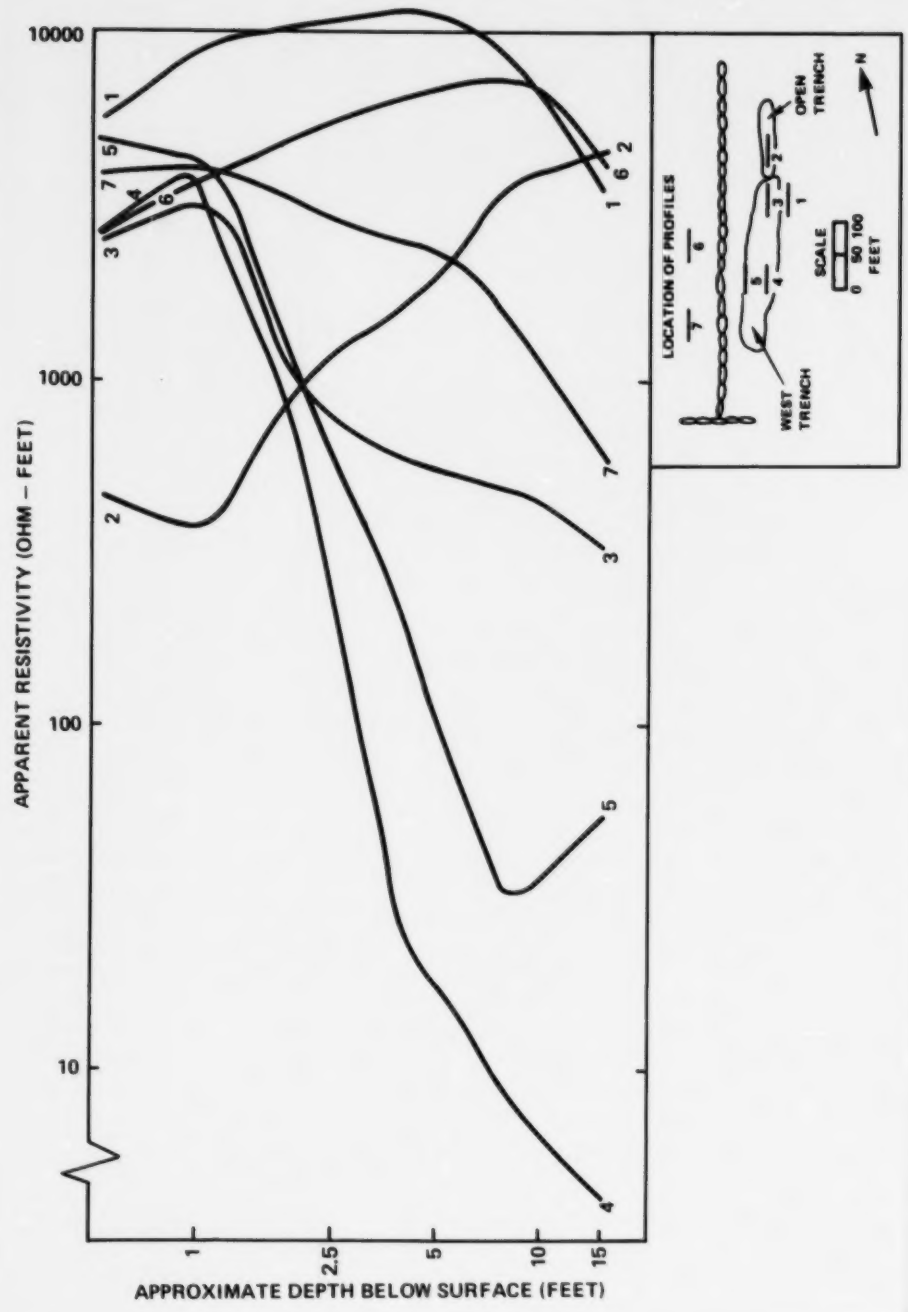


Figure 8. Apparent Resistivity Depth Profiles for Several Locations Near the West Trench

resistivity measured at the location of profile 4. The volume of highly conductive chemicals at this location is inferred as being very large in order to have such a strong effect on the resistivity measurements. A very localized concentration of conductive chemicals would not be expected to have such a strong effect with this particularly wide electrode spacing (32 feet).

Figure 9 shows the same seven profiles, but on a plot of "cumulative" resistivity versus approximate depth below the surface. Slope changes or breaks in the cumulative curves generally indicate the depth to the underlying unit, and the direction of slope change indicates the relative resistivity values of the subsurface materials. Thus, an increasing slope signifies that the underlying unit has a higher relative resistivity, whereby a decreasing slope denotes a lower relative resistivity in the underlying unit. In accordance with the interpretation of Figure 8, Figure 9 shows higher relative resistivities with depth (no contamination) for profiles 1 and 6. Interpretation of profile 2 is more straightforward using the cumulative resistivity plot. Slight decreases in slope, denoting lower resistivity or presence of soil moisture or contamination, are evident between two and five feet and below ten feet. Profiles 3, 4, 5, and 7 show a continued decrease in slope with depth, which is expected because of their locations within the buried drum area or downgradient from the trench.

Determination of the depth of the bottom of the West Trench was not possible using the vertical resistivity plots. It is not clear, however, whether the particular A-spacing used for these profiles (32 feet) was wide enough to allow adequate penetration necessary to detect the bottom of the trench. A second possibility is that there is no detectable change in contamination at the bottom of the trench thereby causing a continuation of the low resistivity readings beyond the region of buried drums.

Fifteen monitoring wells were installed following the lateral resistivity survey. Refusal depths, tentatively assumed to reflect the approximate top of bedrock, did indicate a mound in the bedrock surface off the northwest corner of the site. Four wells in this vicinity were dry, which also gave credence to the results obtained from the resistivity survey, namely the existence and location of two plumes. In addition, soil samples taken from these same locations were much less contaminated than soil samples taken from borings located within the plume boundaries. Consideration of these factors seemed to indicate that ground water flow was being diverted around a bedrock mound and this had resulted in the detection of high apparent resistivity values in this area. It was found by the Phase II bedrock drilling, seismic refraction survey, and chemical analysis of soil and ground water that the bedrock mound did not exist and that contaminated ground water was indeed traveling in this location. In general, the ground water is at a greater depth below the surface in this region than the other surveyed areas, thus resulting in higher relative resistivity values, and subsequent incorrect interpretation.

Although a wider A-spacing (50 feet) was used in this northwest region, the subcontractor failed to calibrate the readings by surveying in uncontaminated areas. It is additionally possible that the 50-foot A-spacing was insufficient to obtain interpretive results due to the depth of the saturated zone (up to 25 feet) in this area and that 70 to 100-foot electrode widths

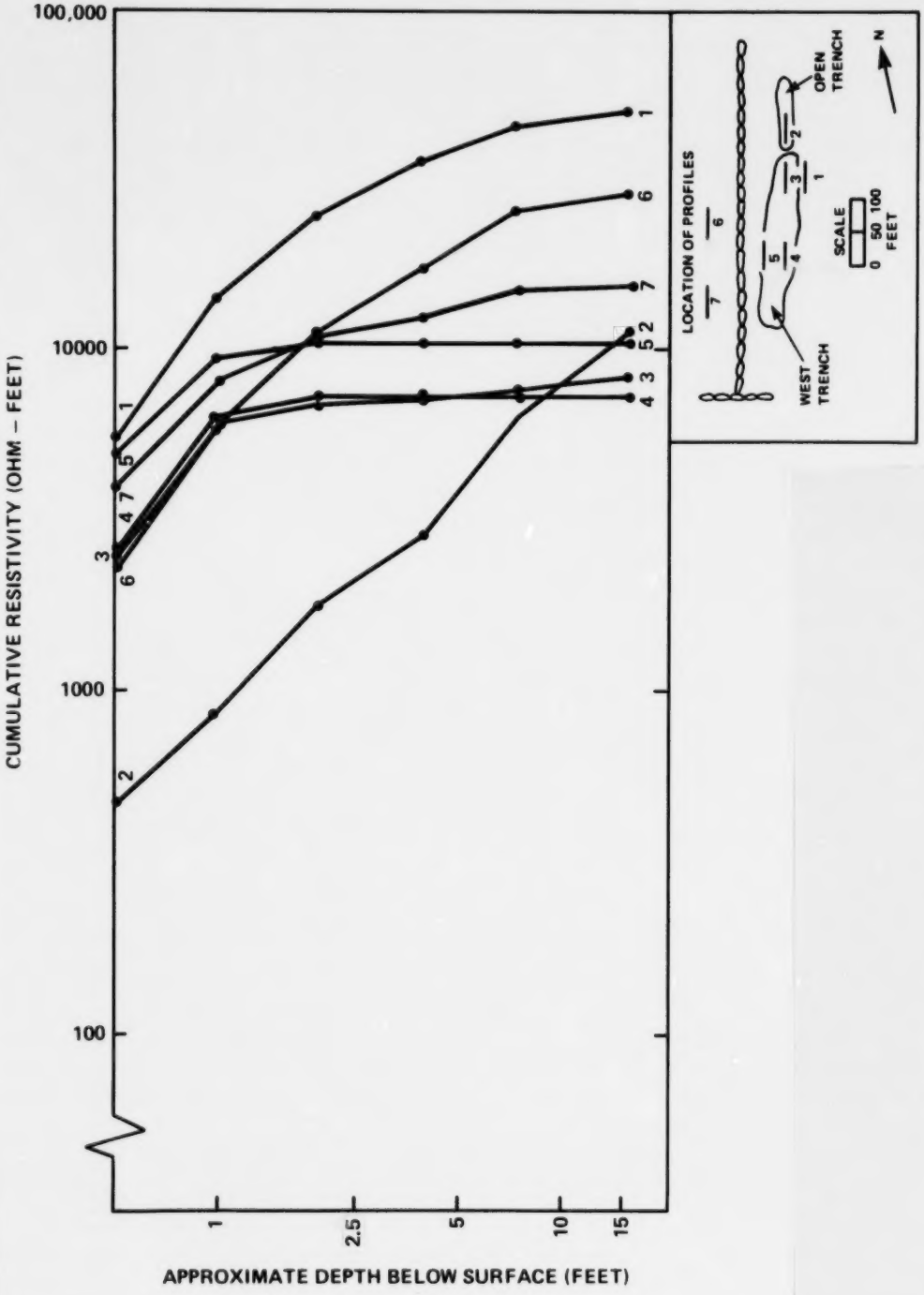


Figure 9. Cumulative Resistivity Depth Profiles for Several Locations Near the West Trench

should have been employed. Lines of current from one electrode to another travel in semi-elliptical paths; because of the path slope, the influence of the saturated zone on resistivity readings decreases in a non-linear relationship with depth. The water table will effect a minor change on resistivity values if it is at or near the maximum extent of the current lines. Therefore, it is recommended for other surveys that the nominal depth of the signal be twice the expected depth of the water table.

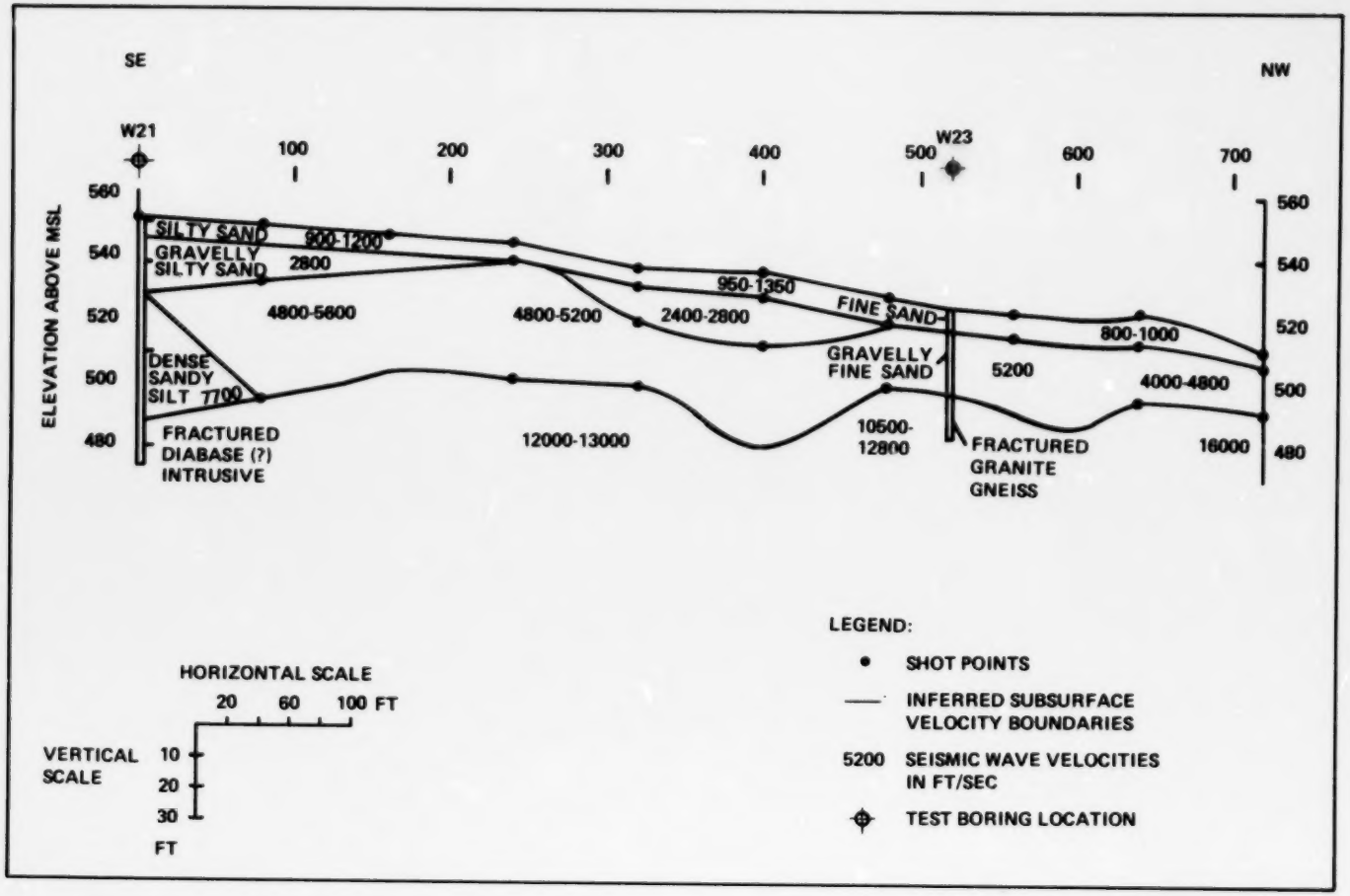
DETERMINATION OF BEDROCK TOPOGRAPHY AND DEPTH OF BURIED DRUMS

Complete verification of the shallow bedrock off the northwest corner of the site was not possible until the bedrock coring and the seismic survey were performed. The drilling showed that the refusal depths of the previous borings had actually been due to boulders and/or very dense till. At each boring location, the bedrock (a granite gneiss) was discovered to be 10 to 30 feet deeper than anticipated. The seismic survey indicated that the bedrock surface was gently rolling, varying from approximately 10 feet below ground surface near the swamp to approximately 70 feet below ground surface on top of the site. Figure 10 shows the seismic profile from W21 through the northwest region of the site (see Figure 3 for approximate location). Subsurface conditions inferred from the compressional wave velocities are given in Table 3. Interpretation of the velocity units is given where correlation with the test borings is possible.

The deep boring drilled in the area between the two plumes (W23) showed that the bedrock was highly weathered and fractured. A piezometer installed in the fractured bedrock indicates that the granite gneiss is hydraulically connected to the unconsolidated glacial deposits. Therefore, ground water is not being diverted around a shallow bedrock mound as had been inferred from the resistivity survey and Phase I drilling, but is actually moving over this area toward the swamp at depths greater than 20 feet. A ground water sample taken from W23 was found to contain a diverse assortment of volatile organic pollutants similar in concentration to samples taken from wells within the two plumes.

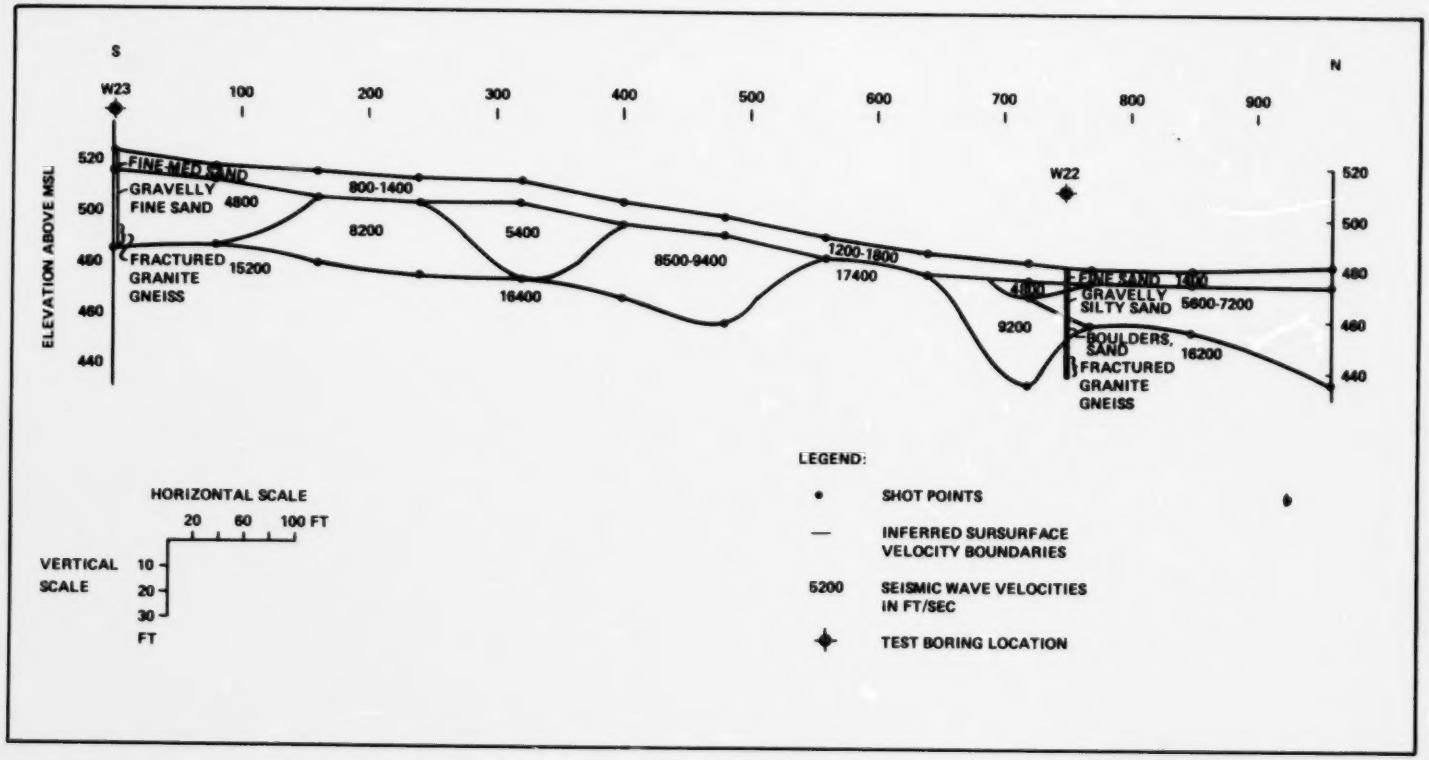
The seismic profiling proved to be most useful for the determination of the depth to dense or competent bedrock, which is the information needed when considering certain on-site abatement alternatives such as source encapsulation or leachate collection trenches. Typically, compressional wave velocities above 11,000 ft/sec are generally indicative of very dense bedrock. Figures 11, 12, and 13 show the remaining seismic profiles taken at the Coventry site to gain information about depth to bedrock. Interpretation of velocity units from correlation with test borings is given where appropriate.

The method of seismic refraction was used over the West Trench in an experimental attempt to determine the depth of the base of the buried drums. Neither ground-penetrating radar nor metal detection was able to show the lower boundary of drums and vertical electrical resistivity measurements revealed no readily-interpretable trends. The importance of knowing the depth of trenches is most clearly shown by the fact that the number of drums estimated in the Northeast Trenches during the Phase I study were significantly lower than what was found during the exploratory excavation. A remote sensing



SOURCE: S.A. ALSUP AND ASSOCIATES, INC.

Figure 10. Results of Seismic Refraction Survey: Line 1



SOURCE: S.A. ALSUP AND ASSOCIATES, INC.

Figure 11. Results of Seismic Refraction Survey: Line 2

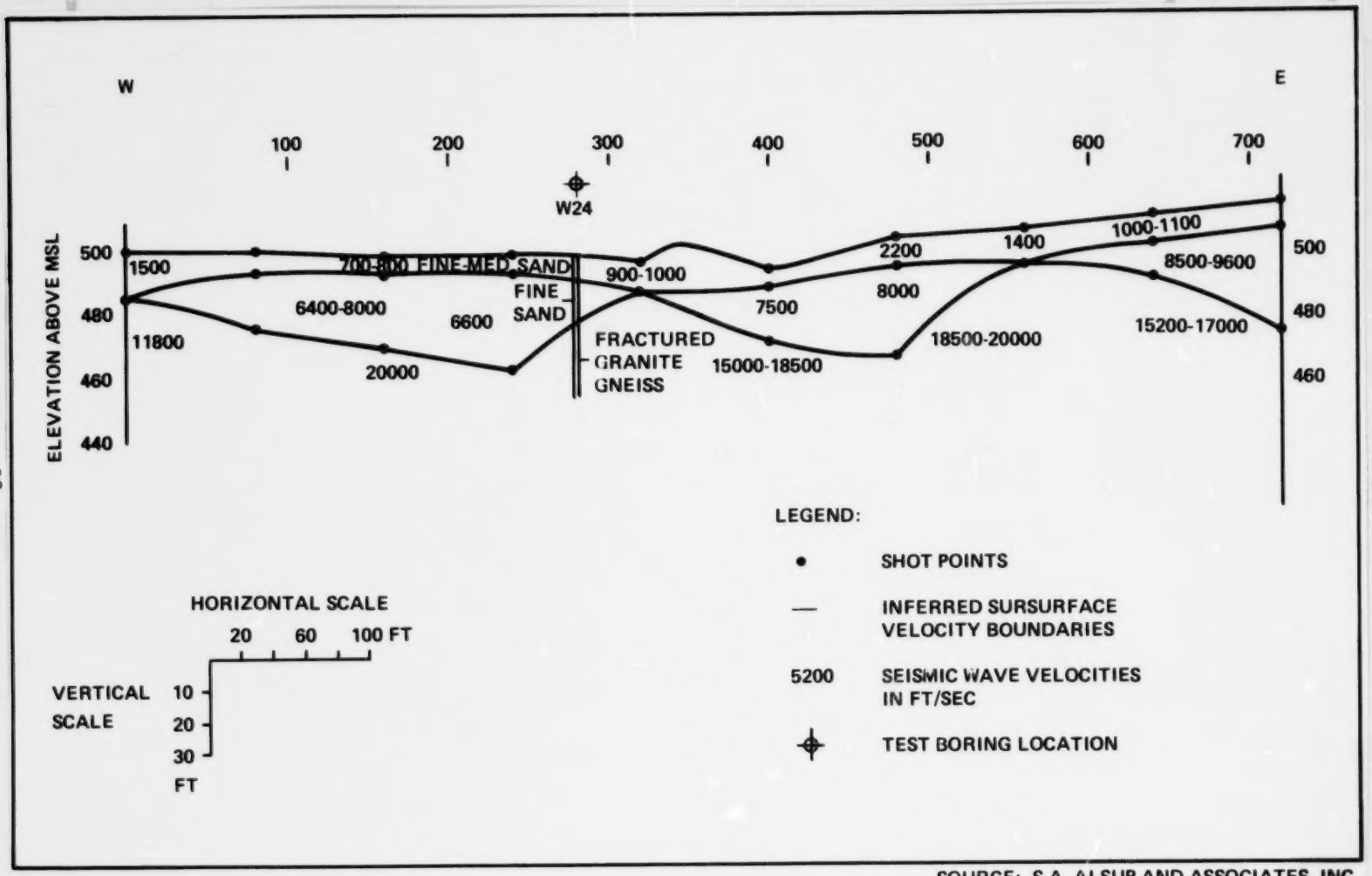


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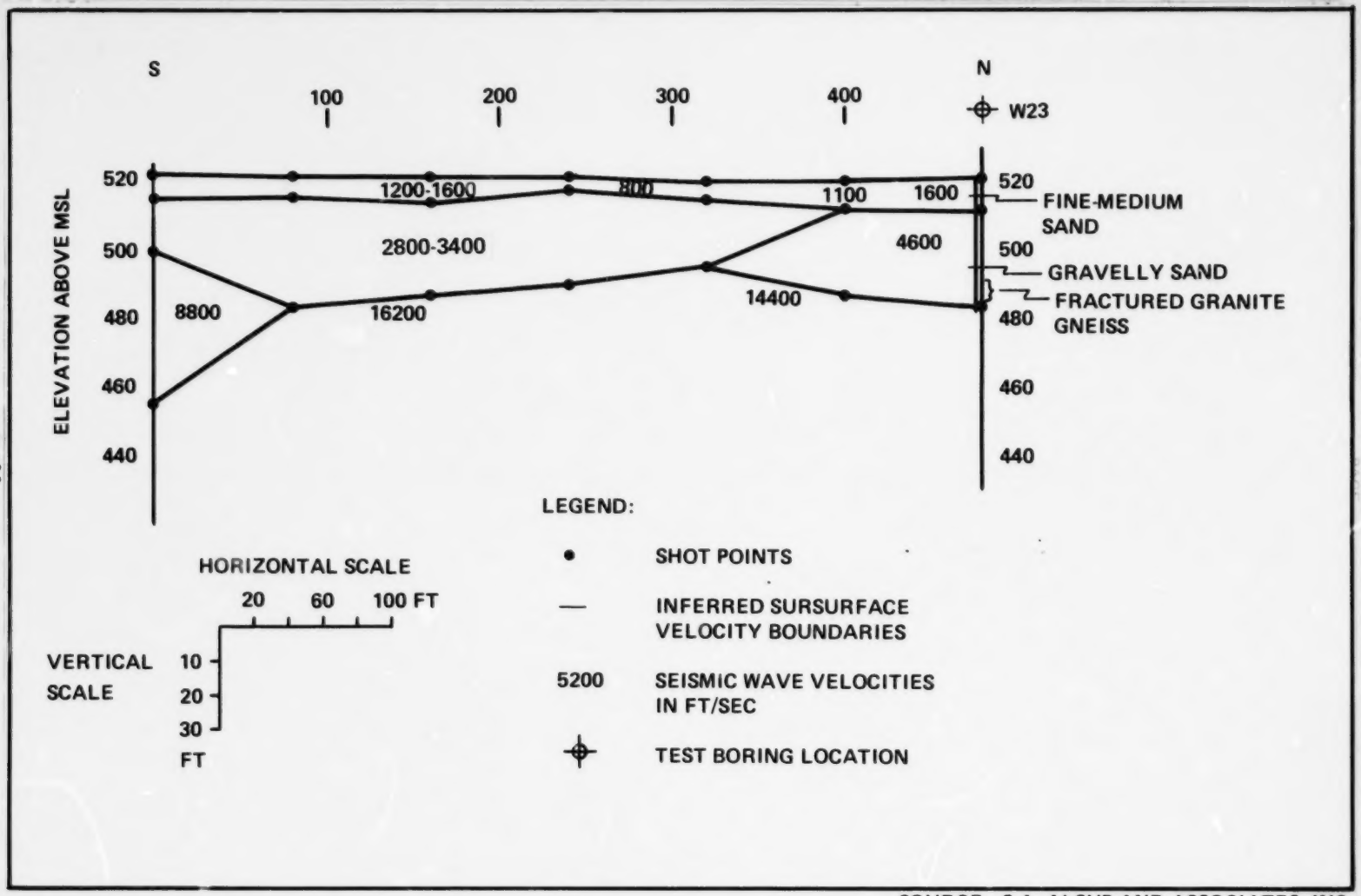
Figure 12. Results of Seismic Refraction Survey: Line 3



SOURCE: S.A. ALSUP AND ASSOCIATES, INC.

Figure 13. Results of Seismic Refraction Survey: Line 4

Table 3

Subsurface Conditions as Inferred from
Compressional Wave Velocities

Wave Velocity (Feet/Second)	Subsurface Conditions
600 - 2,200	Very loose and unconsolidated soil or fill, not saturated with ground water or other fluid, may include ablation tills, very recent sand/gravel deposits.
2,400 - 3,600	More compact deposits than above, but of intermediate density. Often includes non-saturated coarse sands and gravels, some ablation tills, and some compacted fill materials.
4,000 - 5,600	Materials of either type above, with ground water saturation. Degree of saturation and permeability generally increases with increasing velocity to the mid-range values, then may decrease because of finer grain sizes in the deposits.
6,000 - 8,600	Typically dense glacial tills, either with or without ground water saturation. May include deeply weathered or fractured bedrock, with possible marine clays in the lower part of the velocity range.
9,000 - 11,000	Moderately to weakly weathered or fractured bedrock, may include very dense lodgement tills.
above 11,000	Typically very dense to dense sound and competent bedrock units.

Note: There is overlap among the ranges above with regard to the particular type of deposit represented by the compressional wave velocities. Geological interpretation is commonly required for identification of deposit type.

Source: S. A. Alsup and Associates, Inc.

method that can effectively determine depth of drums would greatly aid other similar investigations for the determination of drum number and cost estimates.

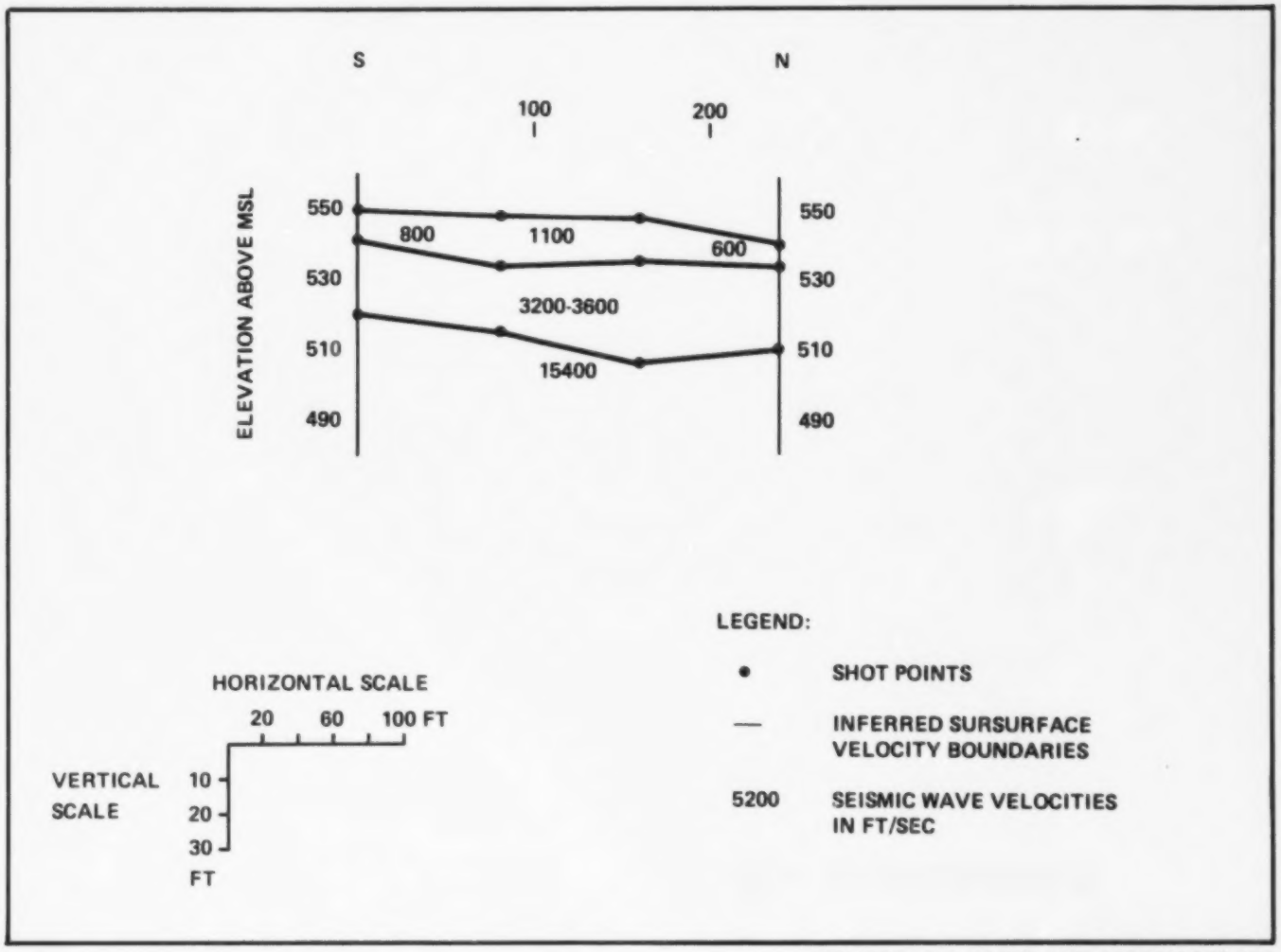
The results of the seismic profile of the West Trench are shown by Figure 14. Three distinct velocity units are shown on the profile and it is believed that the upper one, varying from 7 to 14 feet, represents the disturbed soil surrounding the buried drums.

According to Table 3, the intermediate unit wave velocities (3200 - 3600 ft/sec) shown on Figure 14 do not imply saturated conditions. However, the water table is known to be midway within this intermediate velocity unit (approximately 25 feet below the ground surface). Therefore it is evident that Table 3 presents limited approximations of subsurface conditions and that both the interpretation of the base of the West Trench and the actual characteristics of the 3200 - 3600 ft/sec velocity unit need to be confirmed through test drilling and/or excavation.

DETERMINATION OF TRENCH LOCATION AND GEOMETRY

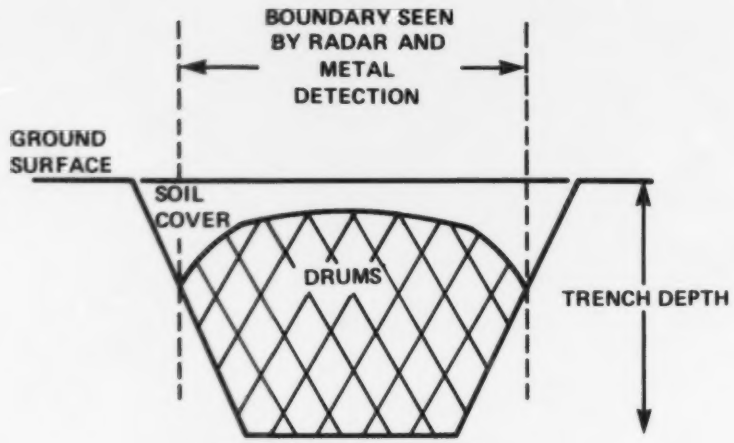
The location and dimensions of the trenches used to estimate the number of drums in each trench were based on a combination of data from metal detection, ground-penetrating radar, and the exploratory excavation. The results from the seismic profiling of the West Trench were used to estimate the lower limit for the bottom of the trenches, even though these data have not been confirmed. Figure 15 illustrates trench geometry with a typical trench cross-section and longitudinal section. For the purposes of estimating the number of drums contained in the trenches, the angle of the vertical side walls was assumed to be 60°, the angle of the declining surface of drums 45°, and the angle of descent at the trench ends 45°. The angle of repose for disturbed site soil is approximately 45°, but excavated side walls were shown to maintain a much steeper slope. Since the radar probed to a depth of 12 feet in contrast with the four to six feet in the vicinity of the trenches for metal detection, the radar would be expected to present a somewhat more accurate indication of trench boundaries. In the case at hand, trench boundaries from the two techniques were compared for each trench. Figures 16 and 17 show this comparison of the areal outlines of the trenches as reported by the subcontractors who conducted the field surveys. Although there is not complete overlap between the outlines determined by the two methods, it is suspected that the deviation is due mainly to inaccuracies in the reporting of the metal detection results. The radar found two trenches in the "Northeast Trench", versus the single trench identified previously with metal detection (Figure 16); the explanation for this is not known. On the other hand, the radar data for the West Trench had to be supplemented by data from the metal detection (Figure 17).

The radar provided, in addition, some useful qualitative information on the way drums were placed and on the trench construction. For example, although there were isolated instances where several drums appeared to be neatly stacked, this was the exception rather than the rule; the drums for the most part appeared to be randomly stacked based on the radar data, and at least in the top eight or so feet below the surface (where individual drums most clearly could be identified) the drums appeared to be present in clusters as opposed

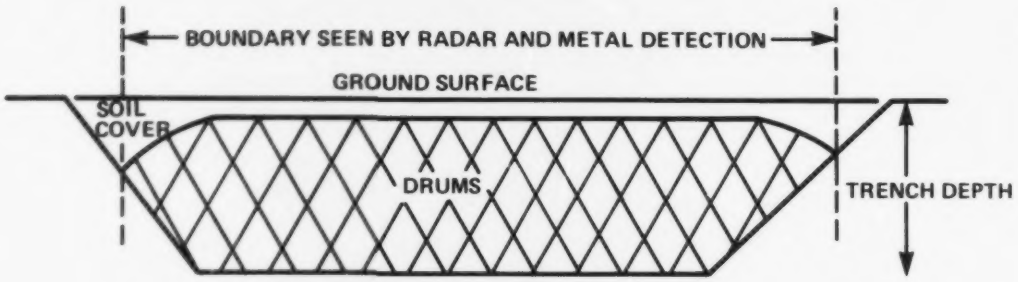


SOURCE: S.A. ALSUP AND ASSOCIATES, INC.

Figure 14. Subsurface Profile of the West Trench as Determined by Seismic Refraction



a. TRENCH CROSS-SECTION



b. TRENCH LONGITUDINAL VIEW

Figure 15. Illustrative Trench Geometry

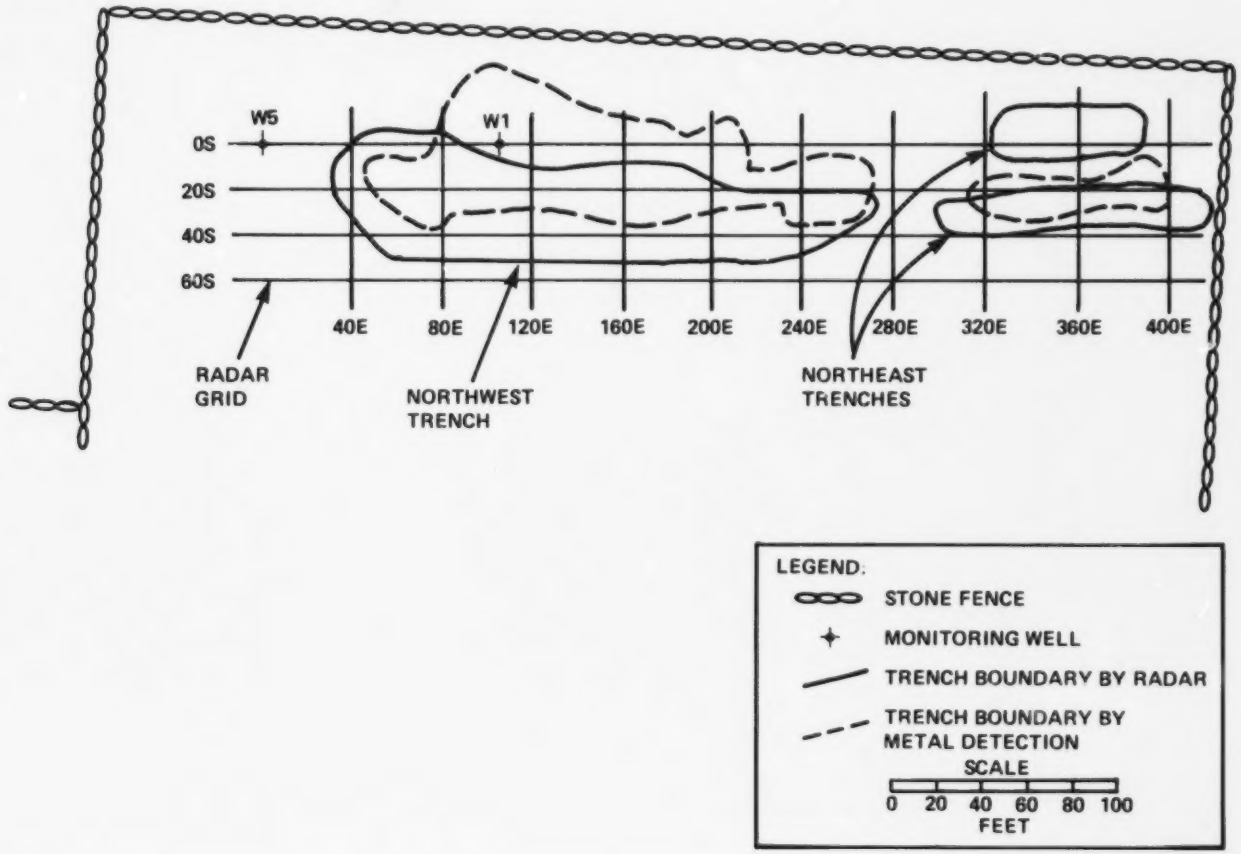


Figure 16. Comparison of Northeast and Northwest Trench Locations as Detected by Ground-Penetrating Radar and Metal Detection

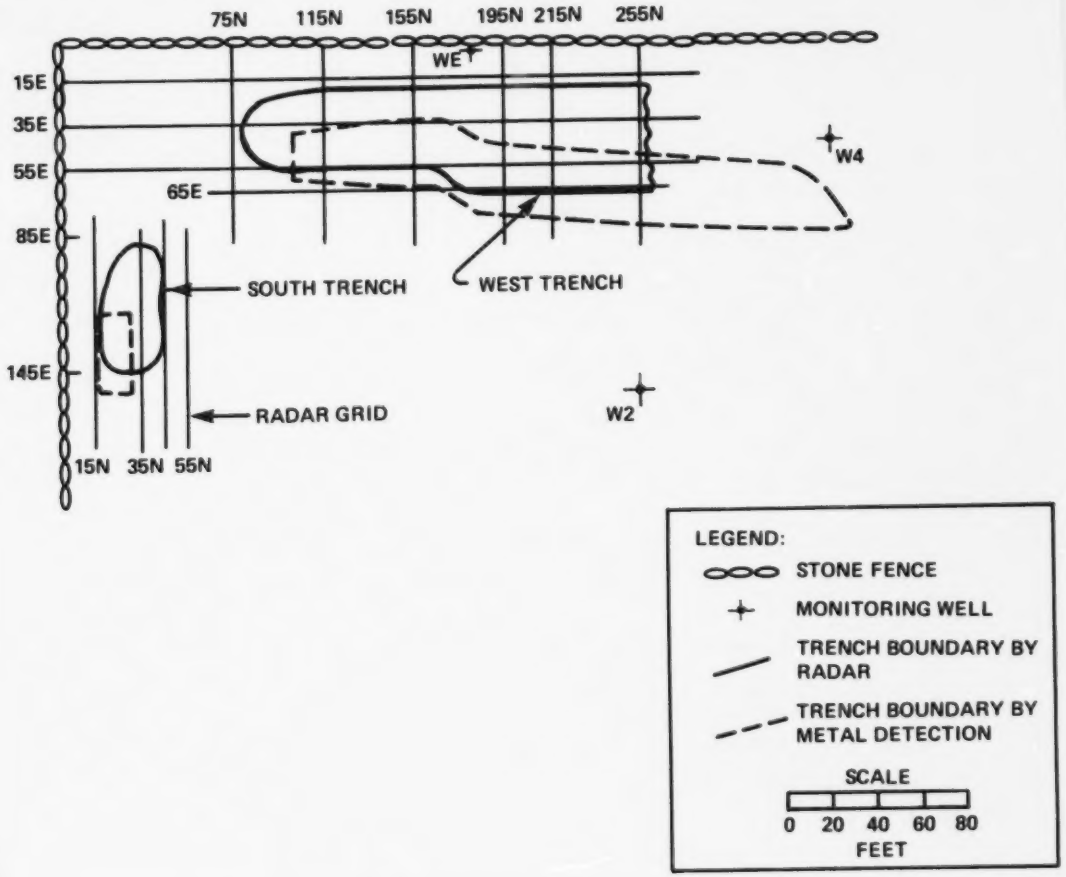


Figure 17. Location of South and West Trenches as Determined by Ground-Penetrating Radar and Metal Detection

to being uniformly dense throughout a trench. Also, the top surface of the drums displayed an "angle of repose" from the sides to the center of the trench cross-section.

The radar was not able to detect the bottom of the trenches, partly because the upper drums masked what was beneath. Even in the West Trench, where a 25-foot nominal depth was probed, the trench bottom could not be located from the data. The radar data can often be used, however, to determine the interface between the sides of the trenches and the undisturbed soil. Radar signals from within the trench are generally stronger than signals from outside the trench. This contrast is attributed to the fact that the disturbed soil within the trench has a higher dielectric constant because it is more porous and has a greater moisture content than undisturbed soil. For future work at other sites, it is suggested that deep radar probing at and just outside a trench boundary may be successful in determining the maximum depth of drums, depending on the steepness of the side of the trench relative to the radar beam, the clarity of the radar signal at this depth, and the subsurface material at the given site.

In order to produce estimates for the number of drums remaining buried, a theoretical trench geometry shown by Figure 15 was employed. It was also assumed for the purpose of the drum estimates that a two-foot layer of soil covered the top of the burial area and two nominal trench depths of 14 and 22 feet were used in order to bracket the range determined from remote sensing and direct excavation.* The bottom of the trenches are assumed to be level with no irregularities. Straight sides for the horizontal widths and lengths have also been assumed; the dimensions used for determining the volumes of each trench are shown in Table 4.

Two densities of drums (percent of volume of drums within trench volume below the cover layer of soil) were used for the drum number estimates: 90 percent and 50 percent. A drum density of 90 percent represents the closest packing arrangement possible for cylinders without regard to interferences imposed by the actual geometry of the trench boundaries.

An exploratory excavation of the Northeast Trenches was conducted by the DEM as a result of Phase I recommendations by MITRE. An actual drum density of 54 percent was calculated for the Northeast Trenches using the results** from the excavation combined with the theoretical geometry shown by Figure 15. The calculated 54 percent density was rounded off to 50 percent for the lower limit calculations of the drum number estimates.

The estimated range of the number of drums remaining buried at the Coventry site is found in Table 5. The drum estimate was performed by calculating the volume of each trench and multiplying the volume by the assumed

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*14 ft - seismic survey of West Trench
22 ft - average depth of deeper Northeast Trenches

**2300 drums removed from two trenches with the following dimensions: Trench A = 120 ft long, 20 ft wide, and 22 ft deep (average), and Trench B = 60 ft long, 15 ft wide, and 17 ft deep (average).

Table 4

Estimated Rectangularized Dimensions of Surface of Trenches

Trench Location	Width (feet)	Length (feet)
Northwest	50	235
West	45	240
South	30	60

Source: Ground-penetrating radar and metal detection survey.

Table 5

Estimated Number of Buried Drums
Based on Extrapolation of Best Available Data

Trench Location	Maximum Drum Density		Drums Randomly Stacked	
	d = 14 ft	d = 22 ft	d = 14 ft	d = 22 ft
Northwest	14,800	22,400	8,200	12,400
West	13,500	20,200	7,500	11,200
South	1,700	2,100	1,000	1,200
Total	30,000	44,700	16,700	25,000

Notes: d = nominal trench depth

Random stacking indicated by results of excavation of Northeast Trenches, approximated by 50 percent drums, 50 percent earth by volume in trench below two-foot cover and assumed trench geometry, as shown by Figure 10.

Drums are assumed to be uncrushed, 55-gallon drums.

drum density to yield the total volume of drums. The estimate for the number of whole drums is provided by dividing the total volume by the volume of a single drum (7.35 cu ft). As Table 5 shows, the overall range varies by a factor of two and a half, from 16,700 to 44,700, while the more likely range based upon the observed depth of the Northeast Trenches is less than a factor of two, from 25,000 to 44,700.

The above estimates are for whole, uncrushed 55 gallon drums. The numbers will necessarily increase if some are crushed, enabling closer packing. Crushed drums, however, are more likely not to contain chemicals in liquid form. The drum number estimates can be corrected for the presence of crushed drums by multiplying by $g/(f + g - gf)$, in which f represents the fraction of crushed drums and g is equal to the ratio of the volume of a whole drum to the volume of a crushed drum. If $g = 2$ and $f = 0.3$, for example, as indicated by the exploratory excavation of the Northeast Trenches, there would be 18 percent more drums (whole plus crushed); however, there would be 17 percent fewer whole drums.

Prior to the radar survey, an estimated range of drums was made which was substantially lower than the estimates presented here. The earlier analysis plausibly assumed that the trenches with buried drums were of similar construction to that of an unfilled trench on the site: nine feet in depth and with sides of slope 45°. As a lesson for other similar sites, it is wise to keep in mind that without the benefit of more accurate information, the "worst case" corresponds to a steep sided trench (with angle of repose depending on local soils as well as the method of trench construction) with depth approximately to the water table, to bedrock, or to the maximum feasible excavation depth.

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SECTION 4

EVALUATION OF THE REMOTE SENSING TECHNIQUES

Section 4 presents an evaluation of the remote sensing techniques employed at the Coventry site, including other potential uses, and the limitations in each case. The above information is presented in summary form in Table 6.

DETECTION OF SUBSURFACE CONTAMINATION

The use of electrical resistivity as a remote sensing technique to delineate the limits of the contamination plume was extremely appropriate at the Coventry site. As described in Section 3, natural conditions at the site were such that the resistivity survey was valuable in locating most of the contaminated ground water for the positioning of monitoring wells. A limitation of the technique, however, is exemplified by the incorrect interpretation of a relatively deep plume off the northwest corner as being an area of ground water diversion.

The following conditions are necessary for using resistivity as a remote sensing technique in a site investigation:

- contrast between the qualities of the contaminated and background ground water, such that the conductivity of one is very different from the other
- relatively shallow depth to the contaminated water body below ground surface, such that conductivity differences within the water body are not masked by overlying strata
- few changes in geology, such that there are no great variations in either the thickness or physical characteristics of the unsaturated zone over the site.

Knowledge of certain man-made interferences, such as buried electrical conductors or paved areas which might mask resistivity contrasts in an otherwise suitable area, is also required. Therefore, a basic understanding of the geologic and hydrologic conditions at the site, as well as adverse man-made conditions, is essential to determine whether or not the resistivity method is applicable.

In addition to determining the extent of contaminated ground water, lateral electricial resistivity profiling may be used to monitor changes in both the quality and position of the contamination with time. This application is most useful in situations where it is necessary to monitor the effectiveness of a particular method chosen to decrease the impact of the contaminant

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Table 6

Comparison of Remote Sensing Techniques

Technique	Purpose	Advantages	Limitations
Electrical Resistivity			
Lateral Profiling	• determine lateral extent of contaminated ground water • facilitate placement of monitoring wells and optimize their number • monitor changes in plume position and direction	• procedure less expensive than drilling • procedure more rapid than drilling • equipment light-weight, able to be hand carried • survey may be conducted in vegetated areas	• limited ability to detect non-conductive pollutants • technique unsuitable if no sharp contrast between contaminated and natural ground water • interpretation difficult if water table is deep • interpretation difficult if lateral variations in stratigraphy exist • interpretation difficult if radical changes in topography are not accounted for in choice of A-spacing • technique unsuitable in paved areas or areas of buried conductive objects
Depth Profiling	• indicate change in contamination with depth • establish vertical control in areas of complex stratigraphy	same as above	same as above
Seismic Refraction (Non-explosive Method)	• determine depth and topography of bedrock • determine depth of trench containing buried drums	• procedure less expensive and safer than coring or excavation • procedure more rapid than coring or excavation • survey may be conducted in vegetated areas	• technique unsuitable if no sharp velocity contrast between units of interest (e.g., trench containing buried drums and surrounding soil) • survey requires access road for vehicle • depth of penetration varies with strength of energy source • low velocity unit obscured by overlying high velocity units • interpretation difficult in regions of complex stratigraphy
Metal Detection	• locate areas of high metal content (e.g., buried drums)	• procedure less expensive and safer than excavation or radar • procedure more rapid than excavation or radar • equipment light-weight, able to be hand-carried • survey may be conducted in vegetated areas	• technique unsuitable for the detection of non-metallic objects • technique unsuitable for objects below five feet • technique unsuitable for determination of number or arrangement of buried objects
Ground-Penetrating Radar	• locate buried objects (e.g., buried drums) • provide qualitative information regarding drum density • detect interfaces between disturbed and undisturbed soil (e.g., bottom of trenches) • detect plumes of high chemical concentration	• procedure less expensive and safer than excavation • procedure more rapid than excavation • procedure deeper-penetrating than metal detection • procedure yields more information than metal detection • procedure may be used over paved areas	• technique unsuitable for vegetated areas • data requires sophisticated interpretation • underlying objects obscured by those above • survey requires access road for vehicle

source(s). In this case, it is not being suggested that resistivity be employed in place of monitoring wells to detect changes in ground water quality, but rather it should be used in conjunction with wells. Consequently, the number of wells required as well as the total cost for the monitoring program may be reduced by this dual system of detection.

Vertical electrical resistivity profiling is used primarily, as it was at the Coventry site, to detect changes in contamination with depth below ground surface at a fixed point. Interpretation of the data is easiest when both the apparent and cumulative resistivity values are plotted, as shown in Section 3. The two curves may be used to locate areas of comparatively higher or lower electrical conductivity, such as where bulk dumping occurred, or to obtain information regarding vertical changes in stratigraphy at sites having lateral variations in subsurface structure. In the latter situation, the depth profiling provides the most valuable information when conducted near a test boring location, so that the resistivity measurements can be interpreted using the geologic log.

It is possible that ground-penetrating radar may also be employed to detect areas of subsurface contamination. The exploratory excavation of the Northeast Trenches showed that plume areas previously identified by the radar survey (blurred areas of Figure 6) were due to nested pockets of liquids. Contaminated areas can be distinguished by radar from both soil and ground water because of the greater signal attenuation caused by their higher (in most cases) dielectric constant.

The use of both of these remote sensing techniques to detect subsurface contamination is limited to areas where pollutants having a high electrical conductivity have been dumped, buried, or improperly stored, such that leakage causes a distinct contrast with background water quality. Future research concerning remote methods of detecting subsurface contamination should be directed toward the identification of a means of detecting non-conductive pollutants, such as organic chemicals which tend to be prevalent at abandoned waste sites.

ELUCIDATION OF BEDROCK TOPOGRAPHY AND CONDITION

The use of seismic refraction as a remote sensing technique applied in ground water investigations is not new. At the Coventry hazardous waste site, seismic refraction was employed to determine the depth to bedrock, to identify channels in the bedrock surface, and to determine the thickness of surficial fracture zones in the crystalline bedrock. Each of these applications has been attempted previously in other hydrogeologic studies. At Coventry, the interpretation of the seismic wave velocities generally showed good correlation with the depth to bedrock as determined by actual rock coring. In addition, the seismic results showed that the bedrock surface undulated, varying from approximately 10 to 70 feet below ground surface. However, no indication of the thickness of surficial fractures in the bedrock surface was possible by the seismic technique, although this is not considered unusual since fractures seen in the core samples were numerous but narrow. Only wide fractures would dissipate the seismic energy sufficiently to be interpreted as "non-competent" bedrock.

There are several advantages, as well as limitations to the use of seismic refraction in determining the bedrock topography. The main advantage, which relates to the simple non-explosive seismic method employed at Coventry, is the relatively low cost as compared to coring as a means of locating and identifying bedrock. Although coring will still be required in order to validate the interpretation of the seismic data, it is probable that the amount of drilling will be reduced since a seismic survey will allow the selection of appropriate and possibly less expensive (shallower) drilling locations.

Seismic refraction surveys are generally limited to areas which have a simple two or three layer structural configuration. Simple stratigraphy aids in interpretation, as well as reduces the amount of direct subsurface sampling necessary. Large contrasts in the seismic velocity of each layer are also essential. Additionally, it should be recognized that the seismic refraction method will not detect a low-velocity layer beneath a high-velocity layer. This is due to the fact that waves refracted downward by the low-velocity layer will never by detected by the surface receiver before waves are refracted upward by the high-velocity layer. The depth of penetration of the seismic method is also limited by the strength of the energy source. However, for shallow (up to 100 feet) investigations similar to the Coventry site the hammer drop method is adequate.

Ground-penetrating radar can also be used to determine the location of the soil-bedrock interface, although this application was not attempted at the Coventry site. In areas of low soil conductivity, the depth range of the electromagnetic impulse can be as great as 30 meters (approximately 100 feet). However, soils having high electrical conductivity inhibit the transmission of the signal, thereby resulting in a decrease in the depth of penetration. Therefore, radar is preferable to seismic refraction only in situations where the depth to bedrock is very shallow (less than 30 feet) and a large survey area must be covered in a short period of time.

DETERMINATION OF SUBSURFACE TRENCH LIMITS

The feasibility of using seismic refraction and ground-penetrating radar to locate the side and bottom limits of the trenches was tested at the Coventry site. Results showed the following:

- radar could be used to locate the side boundary between disturbed and undisturbed soil
- radar was not successful in locating the base of the trenches, which tended to be obscured by the buried drums and by the relatively high moisture content of the overlying material (resulting in a high dielectric medium)
- seismic refraction was only moderately successful in locating the side boundaries of buried drum areas. Differences in velocities were noted between what may be interpreted as inside versus outside the trench, but actual limits to the units cannot be determined without direct subsurface sampling

- an interface that may be interpreted as the base of the trench was located by the seismic refraction method, although additional test borings or confirmation by excavation is necessary for validating the results.

Seismic results from this study or from a controlled experiment must be calibrated with test boring logs to determine if a trench/undisturbed soil interface can be located by the refraction method. The radar technique appears useful in locating side boundaries, but not in the definition of the bottom primarily due to the high attenuation of signal by the trench material (drums, moisture and contaminants). Both techniques are limited by the fact that the results from each require skilled interpretation.

DETECTION OF BURIED DRUMS

Metal detection and ground-penetrating radar were used at the Coventry site to determine the outlines of trenches containing buried drums, and to the extent feasible, provide additional information as to the distribution of the drums. Because the radar has the ability to penetrate deeper than the metal detector, it was assumed that the radar would define the trench outline more accurately. However, a metal detector can easily and inexpensively locate the approximate trench outline using a widely-spaced grid, and then other techniques can be used to focus on the outlined areas. Additionally, the information desired from the metal detection survey is obtained while in the field and does not require extensive interpretation.

Ground-penetrating radar is a feasible method to use to refine boundaries of the trench by providing information on the distribution of buried drums. The technique is not without limitations, however, nor can it be considered the only means available to provide this information. Magnetometry has also been considered for this same purpose, but radar was the technique selected for the Coventry study. Once rough trench outlines have been determined by the metal detector, a magnetometer survey of these approximate areas could be conducted with regular grid spacing (on the order of five feet) to identify the changing signal character at the trench boundaries. Bensen and Glaccum (1980) have shown magnetometry to be successful in identifying the approximate spatial distribution, depth to the "center of mass," and quantity of drums present, in a survey over a linear pile of buried drums about two meters deep.

Other remote sensing methods that have been considered to obtain information on the distribution of drums include various acoustic mapping techniques or "geotomography" (geophysical tomographic techniques) (Eddy and Guttrich, 1979). For maximum sensitivity using the acoustic technique, an acoustic wavelength on the order of 1 to 2 feet (approximately 10 Khz) is required, which is unfortunately within the audible range. The maximum depth of penetration is normally on the order of 50 wavelengths (in this case 50 to 100 feet), which would usually be well in excess of what is required at an abandoned dump site. Depending on drum content (high loss if empty, moderate loss for liquids and low-density powders, least loss for compacted soils), acoustic signals would penetrate through drums at shallow depths, thereby permitting detection of drums at lower depths than with radar. However, multiple reflections could generate display artifacts that might be misinterpreted as drums at excessively great

depths. It is also possible that large boulders could be confused with drums, but as with radar, there may be several methods for distinguishing between the two either in the field or from the data.

Geotomography was also considered by MITRE for defining drum distribution by using cross-borehole probing with either or both acoustic or electromagnetic signals. These procedures would yield substantially higher assurance that all drums had been located, but would involve much higher cost than either radar or acoustic methods for drilling and subsequent computer processing.

Despite the fact that the acoustic technique may be able to view drums buried beneath other drums (if drums and soil were tightly packed) better than the radar method, the latter was selected due to the relative ease of performing the survey. Acoustic mapping techniques require considerably more site preparation since the transducer must be physically coupled to the ground. Although the survey area also should be relatively free of vegetation for a radar survey, the operational problems are much less than for acoustic techniques. Geotomography was considered prohibitively expensive and a magnetometer survey ineffective in determining the information necessary.

As shown previously in Figure 5, the radar technique was able to identify individual buried drums in the trenches. The radar data showed, to an approximate depth of 12 feet, that most of the drums were in a random distribution rather than arranged in orderly stacks. It is suggested that information obtained about drum distribution at the Coventry site be validated by conducting trench excavation in such a manner that data are collected in a rigorous and systematic manner.

The main limitation regarding the use of radar for the detection of buried drums is the requirement for skilled interpretation of the resulting data. As can be seen from Figures 4, 5, and 6 the radar-produced signals are complex and it is difficult to distinguish between reflective objects, such as boulders or drums. Blurriness of the signal is produced from high dielectric constant media, such as ground water or leaking chemicals, thus possibly causing their obliteration (which may be enhanced by computer processing). A significant obstacle to data interpretation arises from the relative inexperience inherent in the use of ground-penetrating radar for buried drum determination. There presently does not exist an adequate data base from various sites to provide signatures of drums in various configurations and arrangements which can be said to be known or proven. Another drawback is that the data interpretation is usually performed out of the field resulting in a delay between the actual survey work and the use to which it is put. Because interpretation is so difficult, research on the "signatures" from known buried drums would be very beneficial. This type of scientific experiment was not feasible at the Coventry site because this was not the intent of the DEM when it conducted the exploratory excavation.

SECTION 5

RECOMMENDATIONS

Section 5 presents recommendations regarding the use of remote sensing techniques in abandoned site investigations and recommendations for research needs.

SYSTEMATIC APPROACH FOR ABANDONED SITE INVESTIGATIONS

Abandoned hazardous waste sites present varying degrees of difficulty to investigators. For example, abandoned sites which are areally extensive, rural (with hindering vegetation), or in areas of complex geology and hydrology, represent troublesome environments for investigation. Therefore it is important to develop approaches for thorough, but rapid and cost-effective assessments of these difficult situations. In most cases, a well designed and executed investigative program will include remote sensing techniques in addition to direct measurement. Premature action to drill wells, collect and analyze various air, water, and soil samples, or perform excavations without careful planning and proper integration of available techniques may result in unnecessary exposure to hazardous conditions and in an inaccurate or incomplete understanding of the total problem.

Remote sensing techniques may be used to provide reasonably accurate assessments of subsurface contamination, the location and extent of buried drums, and other data needs for determining appropriate methods of abatement. It must be stressed, however, that not all critical information can be obtained remotely, since each of the techniques has limitations, both theoretical and site-specific, and consequently, direct sampling should be undertaken at every uncontrolled hazardous waste site.

To accomplish site investigations in the most efficient manner, a systematic approach is necessary to take advantage of the information that can be extracted from remote sensing methods. In addition, a systematic approach allows a reduction in the time and cost, and an increase in the effectiveness of direct sampling.

In general, the following two objectives must be addressed by all investigations at uncontrolled hazardous waste sites:

- determination of the nature and extent of the problem and the resulting effects on public health (both actual and potential)
- determination of environmentally sound and cost-effective methods to effectively abate the problem (if abatement is deemed necessary).

The first activity of any investigation should be the identification of the specific data needed to meet each objective. After this has been accomplished, the various techniques available for data acquisition, both remote and direct, can be evaluated with regard to the type of information that can be obtained from each in relation to the specific conditions at the site. Although not always the case, it may be reasonably assumed that remote sensing techniques should be used in advance of the more direct data acquisition methods of borings, or excavations. This is not intended to imply, however, that all direct sampling should be held in abeyance. There have been numerous instances in which emergency action is dependent upon immediate results from air, water, and soil sampling, and for such cases remote sensing techniques should be used secondarily.

Table 6 of Section 4 summarizes the purpose, advantages, and limitations of each of the four remote sensing methods used at the Coventry site. It is important that this type of information be consulted prior to development of an investigatory program. Even though there are disadvantages inherent to each technique, proper sequencing and phased studies can potentially result in an overall optimized approach. It must be emphasized that as the study progresses, preliminary conclusions will necessarily be modified and the nature of direct sampling activities will need to be evaluated continuously. It is recommended that final conclusions not be drawn solely from the results of remote sensing methods. Direct sample collection should be undertaken for all studies.

Because no single procedure would be appropriate for all abandoned hazardous waste site investigations, the conditions at the Coventry site will be used for the basis of development of systematic procedures with the expectation that some of the concepts can be applied elsewhere, as appropriate. The sequence of activities shown below represent the idealized case and may not have necessarily been followed in actual practice.* This is due to the fact that the exact capabilities and limitations of some of the remote sensing methods (in particular ground-penetrating radar and seismic refraction for determining the lower boundary of buried drums) were unknown at the outset. The Coventry site indeed provided a valuable proving ground for the mix of the remote sensing techniques.

Objective: Determination of Nature and Extent of Problem

The following conditions were posed by the nature of the Coventry site at the outset of the investigation:

- an unknown number of drums buried on a cleared seven-acre site; location of drum burial areas incompletely known
- an unknown quantity of unknown chemicals bulk-discharged into trenches on the site

*The exact investigatory procedures are presented in the Phase I and Phase II reports referenced in Section 1.

- surface discharge of chemicals at a swamp, 1200 feet away and 50 feet lower than the site

- potential for ground water to flow away from the site over an arc of approximately 270°, two thirds of which is moderately vegetated, not including the swamp

- subsurface material consisting of hard, boulder-studded glacial till amid numerous bedrock outcrops.

The following items had to be determined for a comprehensive understanding of the nature and extent of the problem:

- direction, rate, and extent of subsurface migration of contaminants

- location of surface discharge areas of contaminated ground water and the subsequent fate of the contaminants

- identification of most harmful contaminants

- location of areas of contaminated soil and buried drums and determination of the potential of this source of pollutants for long-term release.

An example of a systematic approach to achieve the above objectives is presented in Table 7 and the phasing of site activities is shown by Figure 18. It should be noted that Figure 18 shows a two-phase monitoring well installation and sampling program. The purpose of a phased investigation is to obtain a preliminary understanding of the problem prior to final planning of all direct sampling in order to more effectively guide subsequent activities. Additionally, this figure shows that, in general, remote sensing preceeds direct sampling in order to reduce the time and cost of the latter and to help ensure that the full extent of the situation is identified.

In the case of buried drums, it is suggested that metal detection, rather than ground-penetrating radar, be used to locate the burial areas because of the relatively lower cost and greater portability of the former technique. However, radar has greater penetration and should be used in all areas where drums are suspected, but not found by metal detection. A limited excavation may then be required to gain information about the depth, condition, and contents of the drums so that the concept of total drum excavation and chemical disposal can be evaluated with the other abatement alternatives. Limited excavation was considered feasible for the Coventry site, since total drum excavation did not appear significantly more expensive than other abatement alternatives.

Surface water, ground water, and soil sampling are necessary for any hazardous waste site investigation. Monitoring wells are best located once the extent and direction of the plume have been determined. It is recommended that monitoring wells be placed at the following locations:

- upgradient from the source of contamination (to monitor background conditions)

Table 7

Systematic Approach to Determine Nature and Extent of Problem at Coventry Site

Objective	Data Needs	Investigatory Methods	Comments
1. Direction, Rate, and Extent of Subsurface Contaminants	• determine areal extent of contaminated ground water	• assess hydrogeologic and geologic settings of the site by reconnaissance and study of topographic maps, aerial photographs, and all existing data	• establish permanent field grid for use by all remote sensing surveys; grid locations can be transferred to site map by aerial photography or land survey
		• conduct vertical resistivity profiles in various locations to determine approximate depths of contamination	• choose wide enough A-spacing for lateral survey to minimize influence of variations of anticipated depth to ground water from ground surface
		• conduct lateral resistivity survey choosing A-spacing based on results of vertical resistivity profile	
		• install monitoring wells inside and outside of contaminated zones as defined by resistivity survey for confirmational purposes	
	• determine vertical extent of contaminated ground water	• conduct seismic refraction survey over contaminated area to determine depths to bedrock and vertical subsurface profiles	• use established field grid for seismic survey
		• install cluster wells consisting of borings screened in soil and in bedrock both inside and outside of contaminated zones	• use results of seismic refraction survey to select most economic locations for bedrock borings
			• determine whether vertical gradients exist and whether contaminants are present in bedrock fractures
			• install bedrock wells as a second-phase drilling effort and install any additionally-needed monitoring wells based upon first-phase results

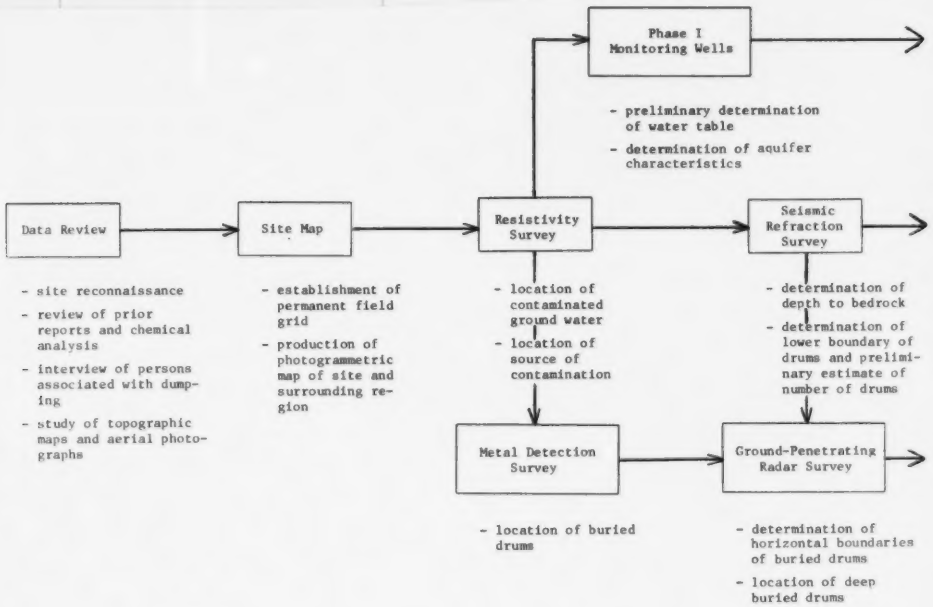
Table 7 (continued)

Objective	Data Needs	Investigatory Methods	Comments
	• determine direction and rate of subsurface migration	• install minimum number of monitoring wells to define ground water flow; well locations should be based on results of resistivity survey and chemical analytical needs (see third objective in this table)	• because the ground surface contours at Coventry site indicate a potentially large arc of subsurface travel, wells at edge of contaminated zones were necessary to detail direction of outer fringe of pollutants
		• perform in-situ permeability tests in selected monitoring and bedrock wells	• install cluster well upgradient of pollutant source to determine background conditions
2. Location of Surface Discharge Areas of Ground Water Contamination and Determination of Fate of Pollutants	• locate surface discharge areas	• reconnoiter site; locate discharge areas by sight and air quality measuring devices	• use air quality measuring devices to determine areas of poor quality, indicating surface discharge points; also indicates areas requiring breathing protection devices
		• use results of electrical resistivity and water table map to identify surface receptors of subsurface discharge	
	• determine fate of pollutants	• conduct downstream sampling, including rate of flow of surface water	• mass balances should be calculated for principal pollutants to determine ultimate dispersion mechanism(s)
		• sample sediment and air around discharge area	• upstream sampling necessary for background conditions
			• all water wells and surface waters used for potable water supplies within a mile radius should be precautionarily sampled
3. Chemical Identification of all Principal Contaminants	• determine principal contaminants	• analyze composite samples from selected wells and surface waters for priority pollutants	• composites made up of wells close to source of pollutants and surface discharge areas: should limit each composite to only two adjacent wells
		• analyze selected wells and surface waters for selected compounds based upon priority pollutant analysis	
	• determine dispersion of contaminants	• select indicator analyses based upon priority pollutant screening: include general water quality tests (pH, conductivity, iron, chloride, TOC)	• indicator analysis provides relatively low cost method for non-specific monitoring of pollutant levels in monitoring well network

Table 7 (concluded)

Objective	Data Needs	Investigatory Methods	Comments
4. Location of Areas of Buried Drums and Contaminated Soil and Determination of Lifetime of Future Release of Chemicals	• locate areas of buried drums and contaminated soil	• reconnoiter site; search for areas of disturbed soil or vegetation, or areas of discolored soil • interview persons involved with dumping activities for information concerning location of trenches and method of operations • study previously taken aerial photographs to obtain historic information • use results of resistivity survey to locate source of contaminated ground water • conduct metal detection survey over all cleared or disturbed areas of site • conduct ground-penetrating radar survey in burial areas located by metal detection survey	• use established field grid for metal detection and ground-penetrating radar survey • metal detection used in advance of ground-penetrating radar because of lower cost and ease of use; however, radar has greater penetration and should be used in all areas where drums are suspected, but not found by metal detection
	• determine lifetime of future release of chemicals	• conduct seismic refraction survey over drum burial area to determine depth of drums • perform limited excavation of buried drums to determine: condition and contents of drums, density of drums, lower boundary of drums • sample soil in drum burial areas and bulk chemical discharge area: analyze extracted leachate for specific chemical compounds determined by priority pollutant screening	• effectiveness of seismic refraction method to determine lower boundary of buried drums remains subject to verification • drum excavation limited to data gathering only and should be terminated when sufficient information obtained; refer to Phase II project report (referenced in Section 1) for recommendations regarding excavation procedures • drum excavation should be conducted after all other site activities completed in order to minimize personnel on site

Note: Coventry site procedures used for illustrative purposes only; investigatory procedures and sequence may not necessarily be directly applicable to other sites.


Phase I Monitoring Wells
- preliminary determination of water table
- determination of aquifer characteristics
Data Review
Site Map
Resistivity Survey
Seismic Refraction Survey
- site reconnaissance
- review of prior reports and chemical analysis
- interview of persons associated with dumping
- study of topographic maps and aerial photographs
- establishment of permanent field grid
- production of photogrammetric map of site and surrounding region
- location of contaminated ground water
- location of source of contamination
- determination of depth to bedrock
- determination of lower boundary of drums and preliminary estimate of number of drums
Metal Detection Survey
Ground-Penetrating Radar Survey
- location of buried drums
- determination of horizontal boundaries of buried drums
- location of deep buried drums

Note: Coventry site procedures used for illustrative purposes only; investigatory procedures and sequence may not necessarily be directly applicable to other sites.

Figure 18. Recommended Sequence

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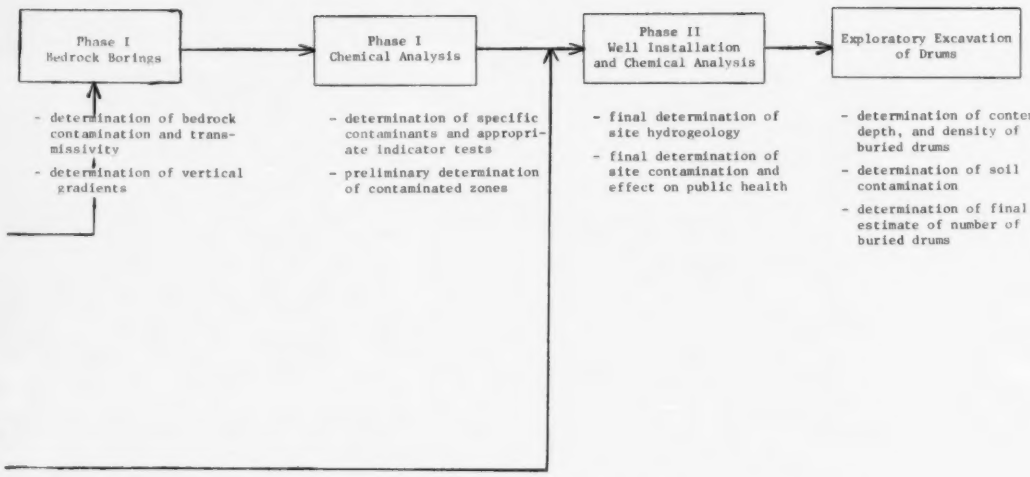
Phase I
Bedrock Borings
- determination of bedrock contamination and transmissivity
- determination of vertical gradients
Phase I
Chemical Analysis
- determination of specific contaminants and appropriate indicator tests
- preliminary determination of contaminated zones
Phase II
Well Installation and Chemical Analysis
- final determination of site hydrogeology
- final determination of site contamination and effect on public health
Exploratory Excavation of Drums
- determination of contents, depth, and density of buried drums
- determination of soil contamination
- determination of final estimate of number of buried drums

of Activities at Coventry Site

- outside of the plume downgradient from the source of contamination (to verify the extent of the plume and to monitor its movement)

- within the plume close to the source of contamination (to obtain samples before extensive dispersion, dilution, or attenuation)

- within the plume at the outer extent of contamination (to observe dispersion, dilution, and attenuation).

It is important to define the depth and topography of the bedrock not only to evaluate certain abatement methods, but also to economically locate the deep borings that may be needed for bedrock sampling, permeability testing, and water sampling. Seismic refraction is a very effective tool for providing remote information on the configuration of subsurface strata. Additionally, the results can be used to locate bedrock wells, the position of which will depend upon the objectives of the investigation. For example, some investigators may wish to install bedrock wells only to determine formation integrity as an acceptable base for certain abatement alternatives. Other investigators may be interested in locating bedrock wells to determine the presence of contaminants in specific regions or channels.

Objective: Determination of Methods to Abate the Problem

As shown in Table 8, the data needs for selecting and determining the cost of abatement alternatives are similar to those for understanding the nature and extent of the problem at the Coventry site. However, the two objectives are best addressed separately, since the locations for direct sampling and remote sensing may differ between the two, as may the use of the information obtained.

It is possible to use remote sensing techniques as a "negative screening" step in the evaluation of certain abatement options. An example of this concept is given in the case of evaluating source encapsulation as an abatement technique for the problem at Coventry. For encapsulation to be feasible, it is necessary to have a low permeability base within a relatively shallow depth from the ground surface. Seismic refraction has the potential to determine whether the bedrock underlying the source of contamination should be ruled out (negative screen) of consideration as an acceptable base. If, after a seismic refraction survey, it is found that the bedrock is either too deep or too fractured to function as an effective base, then rock coring is unnecessary. The information obtained by this method is not sufficient, however, to prove that the bedrock is sufficiently sound for encapsulation without actual test borings and field-permeability tests.

There is one investigational method, estimation of the number of buried drums, listed on Table 7 which is not included in the discussion of the preceding subsection. The remote sensing technique of seismic refraction has the potential to determine the lower boundary of buried drums. The results of an exploratory excavation can be compared to the seismic profile obtained at a particular location and, if valid, the seismic profiles for all other buried drum areas may be used for the drum number estimates. If there is no correlation found between the seismic profile and the excavation (or if an exploratory

Table 8

Major Informational Needs for Implementation of Certain Abatement Activities at Coventry, Rhode Island

Alternative	Informational Needs
Removal of Buried Drums and Disposal of Chemicals	• Drum Condition • Drum Number • Drum Contents • Trench Location and Geometry
Encapsulation of Source	• Drum Contents • Imperviousness of Underlying Strata • Level(s) of Contamination (soil and/or ground water and/or bedrock) • Trench Location and Geometry
Collection and Treatment of Leachate (trenches and/or wells)	• Areal Extent of Contamination • Type of Contamination • Concentration of Contaminants • Imperviousness of Underlying Strata • Aquifer Characteristics
No Action Alternative	• Drum Contents • Drum Condition • Level(s) of Contamination (soil and/or ground water and/or bedrock) • Type of Contamination

excavation is not desired) it is recommended that the maximum feasible excavation depth or depth to bedrock be used for the lower boundary of the buried drums.

RESEARCH NEEDS

As described in the evaluation of the remote sensing techniques in Section 4, each technique has a number of limitations regarding its application at an abandoned hazardous waste site. Several of these limitations define directions for future research, although many of the following recommendations simply involve use of the technique in controlled, research-oriented experimental situations. Recommendations regarding future research into direct sampling methods is beyond the scope of this study. Table 9 presents a summary of the following recommended research needs.

Ground-Penetrating Radar

It is recommended that future research into the use of ground-penetrating radar at abandoned hazardous waste sites be primarily directed toward compiling radar signatures of known buried drum configurations at known depths. It is suggested that this research involve a combination of computer simulation and actual field testing of drums (empty of hazardous chemicals) which were intentionally buried. Additionally, radar signatures should be determined for the following:

- drums buried in average mixed municipal refuse landfills
- drums in good condition versus drums in poor condition
- drums dumped underwater in marshy areas
- drums buried in rubble.

Changes in antenna design would be required in the latter two investigations, as use of the present equipment depends upon relatively even and stable vegetation-free surfaces. It is well known that landfills and wetlands are common locations for the illegal burial of drums, and it would be extremely useful to accumulate, as a data base, the signatures arising from these situations.

In addition to signature research, it is recommended that the usefulness of radar be investigated at secure landfills, in order to determine its effectiveness in determining subsurface conditions; this would be useful to regulatory agencies to verify that proper operations are taking place. It may also be found that the landfill subsurface conditions could be monitored over time using radar techniques. It is also suggested that the applicability of radar to monitoring the stability of physical remedial structures at abandoned hazardous waste sites be investigated.

Research into the area of signal enhancement would be useful for hazardous waste site investigations because of the attenuation of the signal caused by soil moisture. This would enable deeper penetration in moist soils (like

Table 9

Summary of Recommended Research Needs for Remote Sensing Methods for Hazardous Waste Site Investigations

Research Need	Use
Ground-Penetrating Radar	
1. Determine signatures of drums buried under known conditions: • in soil • in municipal refuse landfills • in rubble • underwater • in poor vs. good condition	Compile data base to aid in future interpretation.
2. Determine the effectiveness of radar to monitor subsurface conditions at abandoned sites at which remedial measures have been undertaken and at secure chemical waste landfills.	Observe changes in physical integrity of subsurface structures at secured sites.
3. Develop (or improve) methods of enhancement of reflected signal.	Deeper penetration in moist soils and easier interpretation of complex subsurface problems.
Seismic Refraction	
4. Investigate under controlled experimental conditions whether the technique is effective for determining the lower boundary of buried durms.	Determine the lower boundary of buried drums to estimate total number of buried drums.
5. Determine the effectiveness of seismic refraction to determine the subsurface structures of refuse landfills and secure chemical waste landfills.	Observe changes in physical integrity of subsurface structures at secured sites.
Electrical Resistivity	
6. Determine the effectiveness of electrical resistivity to monitor subsurface conditions at abandoned sites at which remedial measures have been undertaken and at secure chemical waste landfills.	Observe changes in physical integrity of subsurface structures at secured sites.
7. Determine the effectiveness of electrical resistivity to locate and monitor subsurface spills of nonconductive chemicals.	Register the presence of petroleum leaks into an aquifer.

those in New England) and may have added benefits related to interpretation of complex situations.

Seismic Refraction

A comprehensive investigation into the usefulness of seismic refraction as a tool to locate subsurface interfaces, such as trench bottoms, at abandoned hazardous waste sites should be made. In addition to expanding the use at hazardous waste sites, experiments with the technique should be conducted at municipal refuse landfills or secure landfills to determine the feasibility of locating waste depths or cell structures or of monitoring the integrity of engineered remedial actions.

Electrical Resistivity and Metal Detection

The usefulness of electrical resistivity and metal detection in specific applications is widely recognized, and increased use in defining subsurface contamination and locating buried metal objects at abandoned hazardous waste sites can be expected. Additional applications for electrical resistivity should be investigated, such as determining the ability of the technique to monitor pollution from secure landfills or the effectiveness of in-site abatement measures. It is also recommended that improvements be made in the detectability of each technique, specifically in the depth of penetration for metal detection and the use of electrical resistivity where the resistivity of the polluted water is less than that of the background water.

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APPENDIX A

SUMMARY OF CONCLUSIONS, RECOMMENDED ACTIONS, AND COMPARISON OF ABATEMENT ALTERNATIVES: PHASE I

Phase I Investigation: Summary of Conclusions

Chemical Contamination

- Ground water and surface water are contaminated with chlorinated and non-chlorinated organic chemicals (total concentration less than 100 ppm).
- Air quality near the swamp is degraded due to release of chlorinated and non-chlorinated volatile organic chemicals.
- Soil around the site is contaminated with phthalate esters (total concentration less than 20 ppm).

Health Effects

- The chemicals detected are potentially hazardous, but the principal potential threat to health appears to result from poor air quality in certain sections of the swamp.
- The rural nature of the affected area reduces the threat to public health, unless Whitford Pond is contaminated.

Hydrology and Buried Drums

- A bedrock mound located off the northwest corner of the site diverts leachate into two primary plumes; however, both plumes discharge to the swamp.
- The quantity of contaminated ground water flowing away from the site is less than 260,000 gal/day.
- Drums are buried in two major trenches, one along the western and one along the northern boundary of the site.
- The best estimated range of the total number of drums buried is 3,500 to 9,000.

Abatement Options

- The estimated costs of long-term abatement alternatives range from $750,000 to $2,970,000 (February 1980 dollars), but may go significantly higher if specific chemicals such as PCBs are found in sizable quantities.
- Information available at the present time is not sufficient to accurately determine the most cost-effective solution.

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Phase I Investigation: Recommended Actions

	Activity	Purpose	Time Frame (1980)
1.	Post contaminated areas of dump and swamp	Alert trespassers to threat to public health	April
2.	Analyze quantity and quality of influent to Whitford Pond	Determine potential threat to public health	April
3.	Analyze residential wells (within 1 mile radius of site) for volatile organics	Determine potential threat to public health	April
4.	Sample air quality around swamp	Determine nature of hazard	Periodically
5.	Evaluate need to restrict access to contaminated area of swamp	Determine if nature of potential hazard justifies cost of fencing contaminated regions of swamp	Periodically
6.	Excavate and dispose of drums in northeast trench (backfilling with aerated soil)	Confirm continued existence of source of chemicals	April - August (including procurement)
7.	Install absorbent booms and sheets at several locations and evaluate their effectiveness	Limit potential of surface pollutant flow to Whitford Pond	April - May (installation only)
8.	Examine bedrock for presence of fractures and contamination	Assist in the design of long-term abatement measures	April - June
9.	Install additional wells	Define plume boundaries and investigate swamp underflow of contaminants	April - June
10.	Sample existing wells	Monitor changes in water quality	Periodically
11.	Analyze condition of Whitford Pond (aquatic life, surface water, and sediment)	Determine potential threat to public health	April - June
12.	Determine all uses of Whitford Pond water in addition to cranberry irrigation	Determine potential threat to public health	April - May
13.	Conduct detailed evaluation of long-term abatement approach and implementation plan for preferred approach	Abate pollutants in a cost-effective manner	July - September

Comparison of Abatement Methods at the Conclusion of Phase I

Alternative	Key Advantages	Key Disadvantages	Additional Information Required to Implement Alternative	Technique to Obtain Information
1. No Action	• effective if source of contamination is exhausted • effective if total mass of contaminants volatilizes in swamp, the swamp remains isolated, and Whitford Pond is unaffected	• does not remove source of pollutants • potential for future release of pollutants still exists • uncontrolled release of pollutants may cause public health problems	• condition of source (drums) • state of nearby pond • contaminant underflow at swamp • ultimate disposition of all pollutants	• radar, exploratory excavation • additional wells, chemical analysis of soils and water samples
2. Drum Removal and Disposal (excavation, testing, and proper disposal of drums and contents, and contaminated soils)	• remove source of pollutants	• ineffective if drums are ruptured and chemicals dispersed • potential for injury to workers exists	• condition of source (drums) • condition of soil	• radar, exploratory excavation • exploratory excavation, chemical analysis of soil samples
3. Site Encapsulation (construction of impermeable barriers around source of pollutants)	• stops/controls pollution at source • working conditions safer than for drum removal	• does not remove source of pollutants • potential for future release of pollutants still exists • success of containment requires absence of fractures in bedrock surface • requires periodic and perpetual monitoring and maintenance	• condition of source (drums) • condition of bedrock	• radar, exploratory excavation • seismic refraction, core drilling, deep wells
4. Leachate Collection and Treatment				
a. Limited Option (interceptor trenches constructed adjacent to site walls)	• controls pollution at source • working conditions safer than for drum removal	• does not remove source of pollutants • success of collection depends on condition of bedrock • treatment system does not remove all contaminants from leachate • unknown and potentially large life-cycle cost	• condition of source (drums) • condition of bedrock	• radar, exploratory excavation • seismic refraction, core drilling, deep wells
b. More Complete Option (interceptor trenches constructed 600 ft downgradient of site walls)	• controls pollution at source including additional downgradient contaminated soil • working conditions safer than for drum removal	• same as above	• same as above	• same as above

APPENDIX B

SUMMARY EVALUATION OF LONG-TERM ABATEMENT OPTIONS: PHASE II

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SUMMARY EVALUATION OF LONG-TERM ABATEMENT OPTIONS

Long-Term Option[a]	Summary Evaluation
Option 1: Encapsulation	Not Recommended • significant source of chemicals in liquid state (perpetual threat for environmental release) • deep bedrock (high cost) • fractured bedrock (too permeable for secure base)
Option 2: Interceptor Trenches	Not Recommended • deep bedrock (high cost) • irregular bedrock surface (high) cost) • fractured bedrock (too permeable for secure base)
Option 3: Drum and Chemical Removal - with continued monitoring of plume and swamp	Recommended • source of contaminants removed • dispersion of contaminants in ground water monitored
No Action Alternative	Not Recommended • significant source of contamination (potential for long-term continuous release) • swamp not proved to be treatment mechanism (potential for spread of contaminants resulting in human contact)

a. Cost of each option is different than shown in Phase I report although titles of options are the same.

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